Report of Investigations No. 115

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Bureau of Economic Geology • W. L. Fisher, Director
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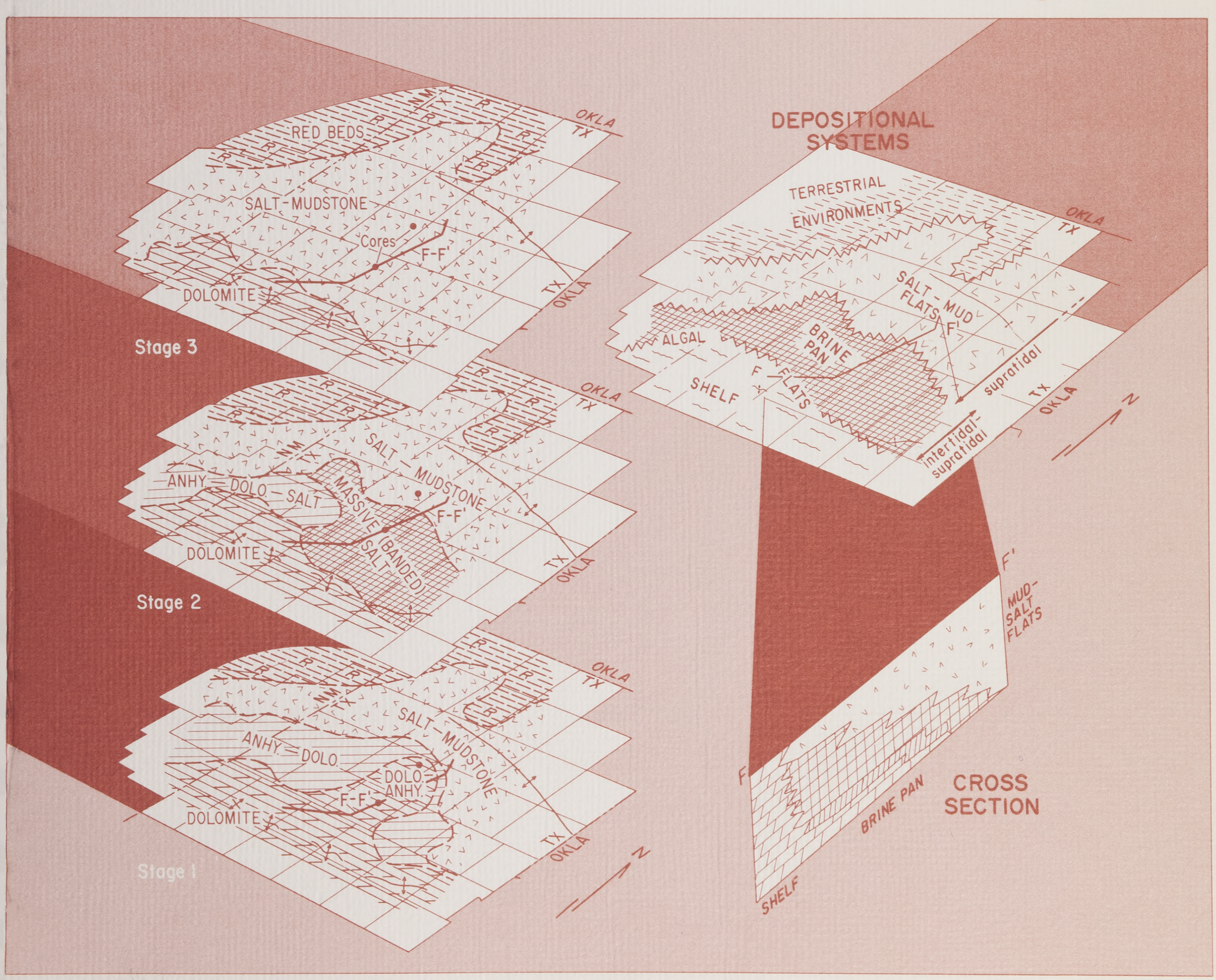

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ABSTRACT

Red beds, evaporites, and carbonates of the upper Clear Fork and Glorieta Formations (Permian) of the Texas Panhandle form an association of facies deposited in nearshore and supratidal environments along an arid coastline. Carbonates were deposited in inner-shelf depositional environments and exhibit upward-shoaling, sabkha-like successions of dolomitic mudstones containing nodular anhydrite. Landward of the shoaling carbonates was a vast salt plain, or sabkha, in which evaporites were deposited in supratidal brine pans and salt flats. Brine pan environments on the seaward parts of the salt plain were intermittently flooded by periodic tides or ground-water seepage. Deposits of gypsum and relatively pure halite formed in the shallow ponded waters. Salt-flat environments landward of brine pans were exposed for long periods of time. Evaporites in salt-flat environments were deposited in surficial salt crusts and interstitially in previously deposited carbonate, evaporite, or clastic host sediments. A common salt-flat facies is red siliciclastic mud in which displacive growth of halite crystals created chaotic mixtures of mud and salt. The development of broad mud-rich tidal flats that extended across most of the study area periodically terminated evaporite sedimentation.

The upper Clear Fork and Glorieta Formations are considered a single lithogenetic unit. Together these units define a broadly regressive cycle of deposition characterized by an increase in supply of clastic sediments through time. During the time of upper Clear Fork deposition, evaporite and carbonate depositional systems were predominant in the Texas Panhandle. In Glorieta time, clastic environments migrated basinward, and mud-flat and salt-flat facies were deposited across much of the Texas Panhandle. In addition to the broad cycle of regression that characterizes the upper Clear Fork-Glorieta lithogenetic unit, there were multiple cycles of inner-shelf, brine pan, and salt-flat facies, which are a record of shorter term fluctuations in the pattern of sedimentation. These cyclic facies patterns were controlled by a delicate dynamic balance among competing processes of basin subsidence, eustatic sea-level variation, clastic sediment supply, and aggradation/progradation of intertidal and supratidal sediments.

INTRODUCTION

The upper Clear Fork and Glorieta Formations (Permian) of the Texas Panhandle are composed of dolomite, evaporites, and red beds (figs. 1 and 2). This association of rock types appears to be a unique facies assemblage, characteristic of nearshore and supratidal sedimentation along an arid coastline. Seaward facies in upper Clear Fork-Glorieta rocks are predominantly dolomitic mudstones that contain nodular anhydrite and exhibit upward-shoaling successions of facies similar to those observed in modern coastal carbonate sabkhas (fig. 3). Evaporites, predominantly bedded salt and anhydrite, were deposited landward of the shoaling carbonates on a vast salt plain, or sabkha. Supratidal brine pan lakes on the seaward parts of the salt plain were intermittently flooded by tides, ground-water seepage, or both. Deposits of gypsum and relatively massive deposits of salt formed in these shallow ponded waters. Landward of brine pans were relatively exposed salt flats. Deposition of evaporites in salt flats was in salt crusts and was interstitial in previously deposited clastic, evaporite, and carbonate host sediments. Periodically, evaporite sedimentation was terminated by the development of broad, mud-rich tidal flats that extended across the entire salt plain (fig. 4).

This report examines the studies of these facies. The upper Clear Fork and Glorieta Formations are considered a single lithogenetic unit. Together these formations define a broadly regressive cycle of deposition (figs. 2 and 5). During the time of deposition of the upper Clear Fork Formation, evaporite and carbonate depositional systems were predominant in the Texas

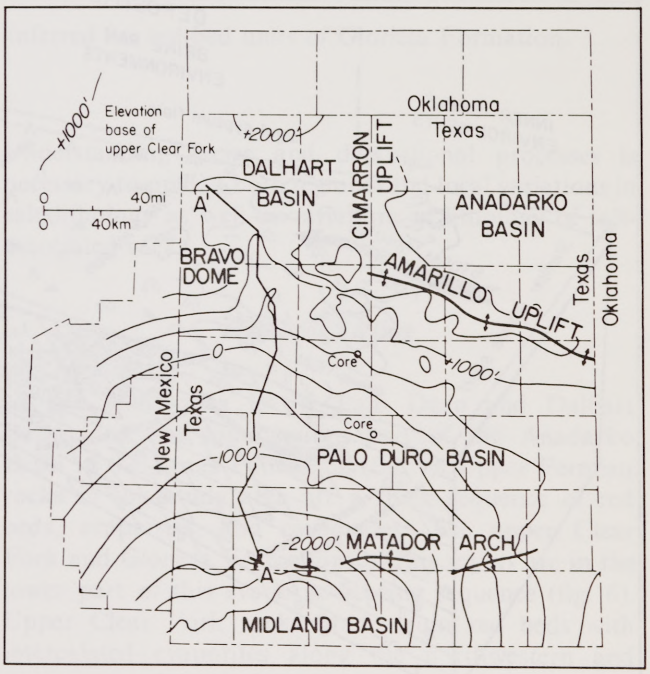


Figure 1. Regional structural setting of Palo Duro and Dalhart Basins. Structural contours are on base of upper Clear Fork Formation.

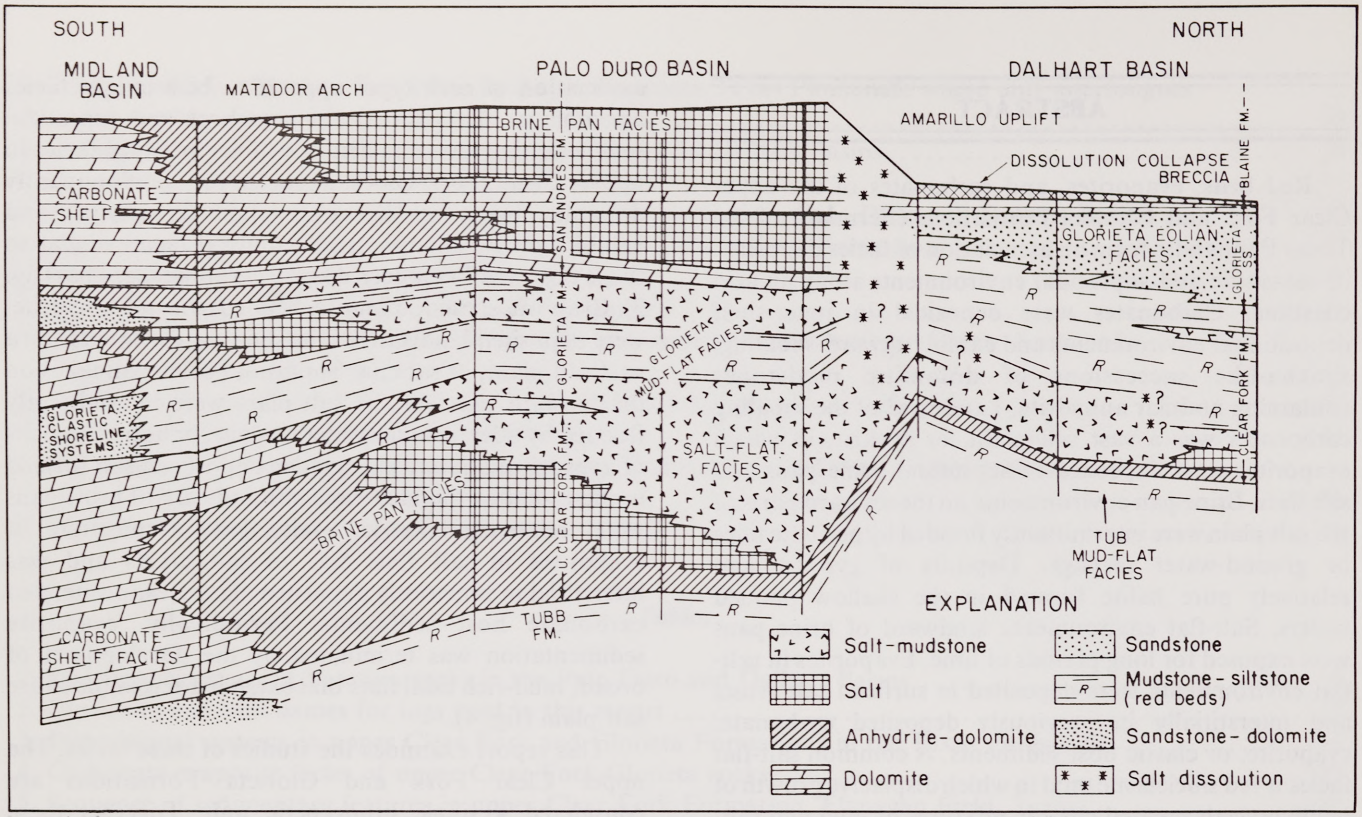


Figure 2. Diagrammatic north-south cross section of upper Clear Fork and Glorieta Formations and underlying and overlying units in Texas Panhandle. Generalized facies interpretations are shown. Location generally follows line of section A-A′ in figure 1.

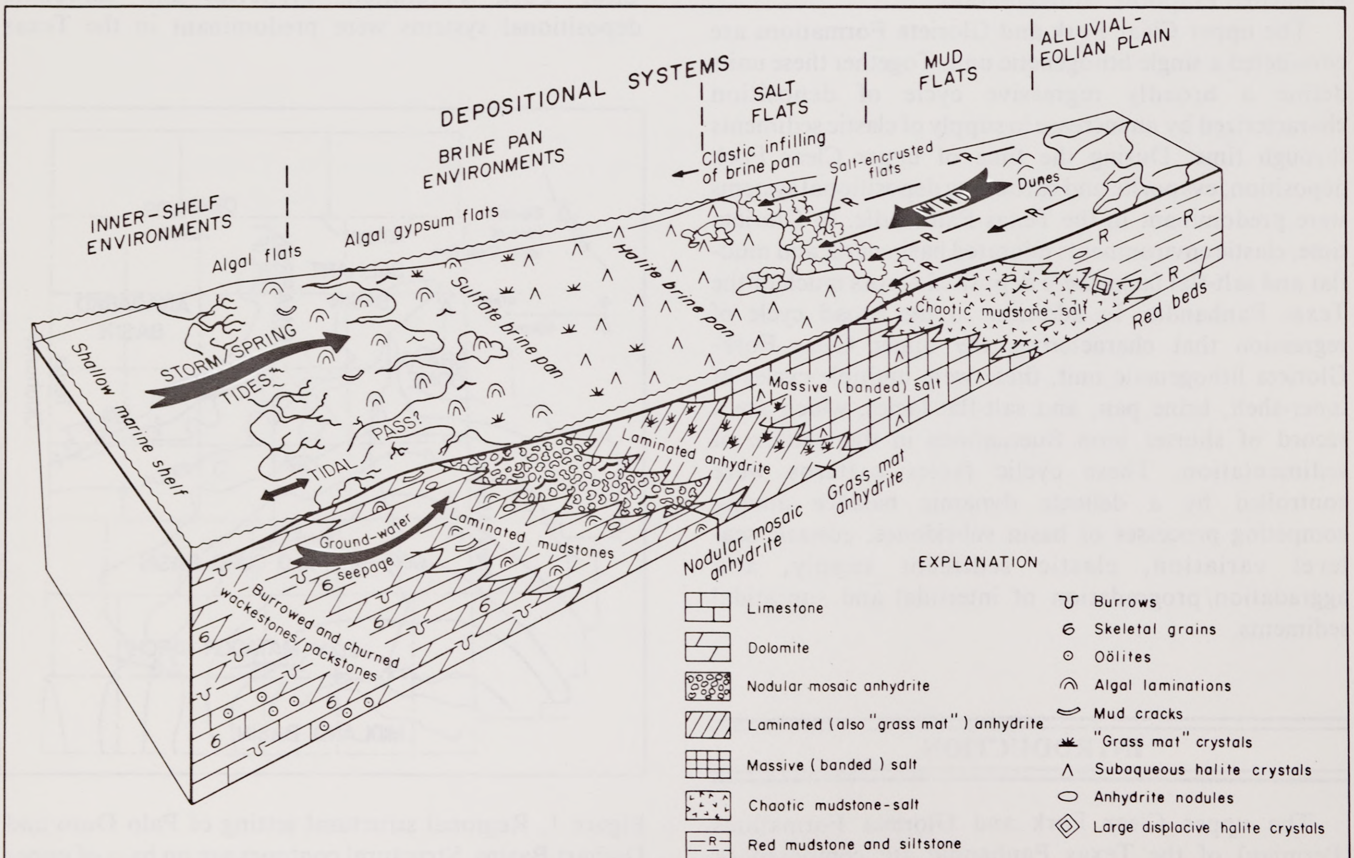


Figure 3. Evaporite and carbonate depositional facies and environments inferred for upper Clear Fork and Glorieta rocks.

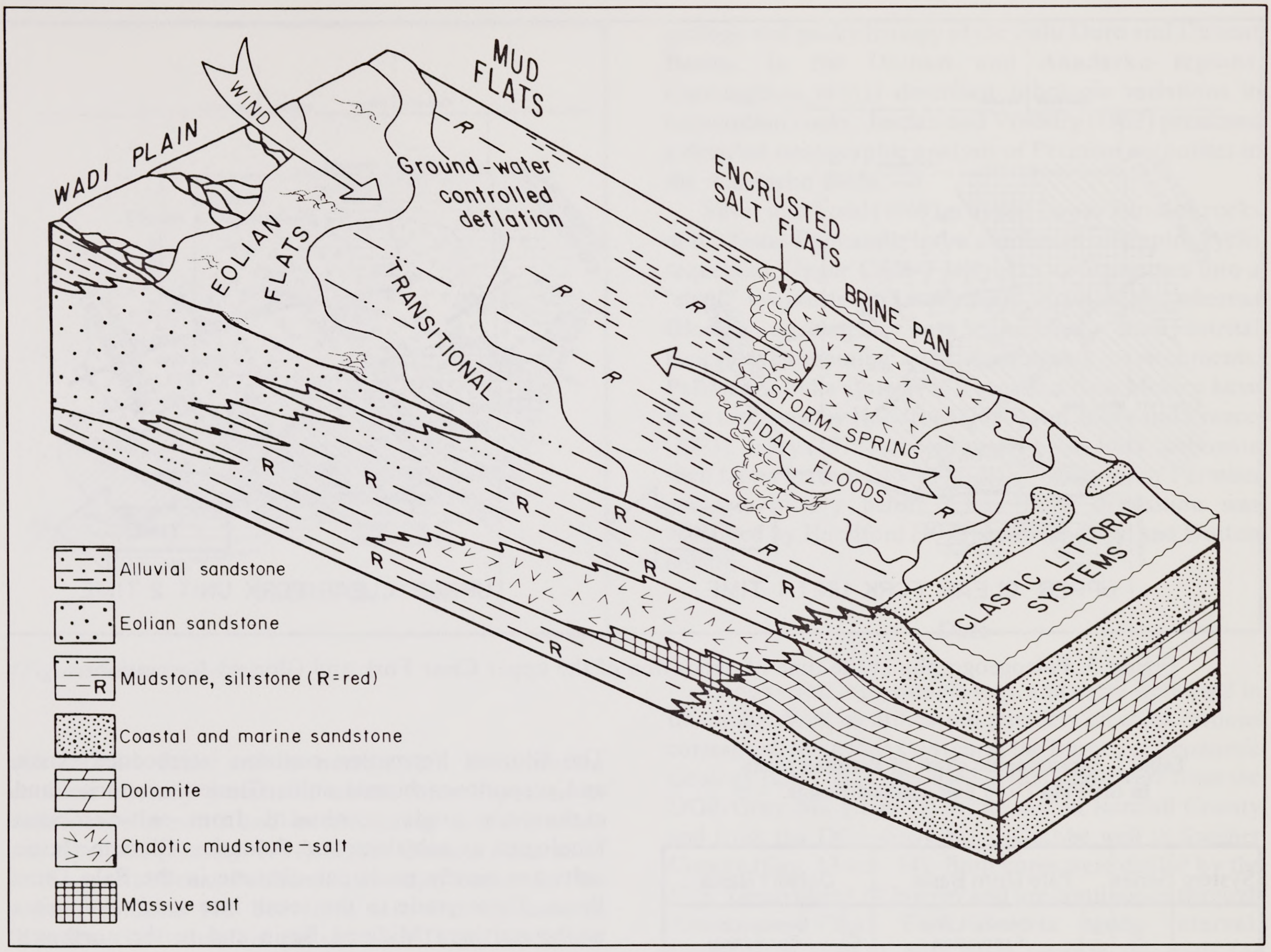


Figure 4. Clastic depositional facies and environments inferred for red-bed units of Glorieta Formation.

Panhandle; red beds were deposited to the northwest and east in mud flats and terrestrial environments. In Glorieta time, clastic environments migrated basinward. Glorieta deposition was mainly in mud and salt flats, which extended across much of the Panhandle. These changing facies patterns were controlled by changes in a delicate balance among competing processes of basin subsidence, aggradation/progradation of intertidal and supratidal sediments, clastic supply, and eustatic sea-level variation.

A discussion of regional setting and stratigraphy, previous studies, and the data base for this research is followed by an analysis of four major depositional systems: (1) inner-shelf, (2) brine pan, (3) salt-flat, and (4) mud-flat systems. Changes in distribution of these depositional systems through time are discussed in a section on geologic history.

This study, funded by the U.S. Department of Energy, is part of an integrated regional analysis of bedded salt in the Texas Panhandle. The purpose of this research is to evaluate the feasibility of using Permian salt beds for deep-subsurface isolation of nuclear wastes. Understanding facies and depositional processes is necessary to predict both regional and local variations in salt lithology as well as variations in lithology of salt-associated rocks.

Regional Setting

The study area is the Palo Duro and Dalhart Basins and the southwestern part of the Anadarko Basin in the Texas Panhandle (fig. 1). Upper Permian rocks in this study area are a thick sequence of red beds, evaporites, and carbonates. The upper Clear Fork and Glorieta Formations of this report are in the lower part of this evaporite-bearing sequence (fig. 6). Upper Clear Fork rocks grade from red beds with intercalated evaporites along the northwestern and eastern margins of the study area to salt-dominant facies in the north-central part of the study area. Salt beds progressively intertongue to the south with bedded anhydrite and dolomite (figs. 7, 8, 9, and 10).

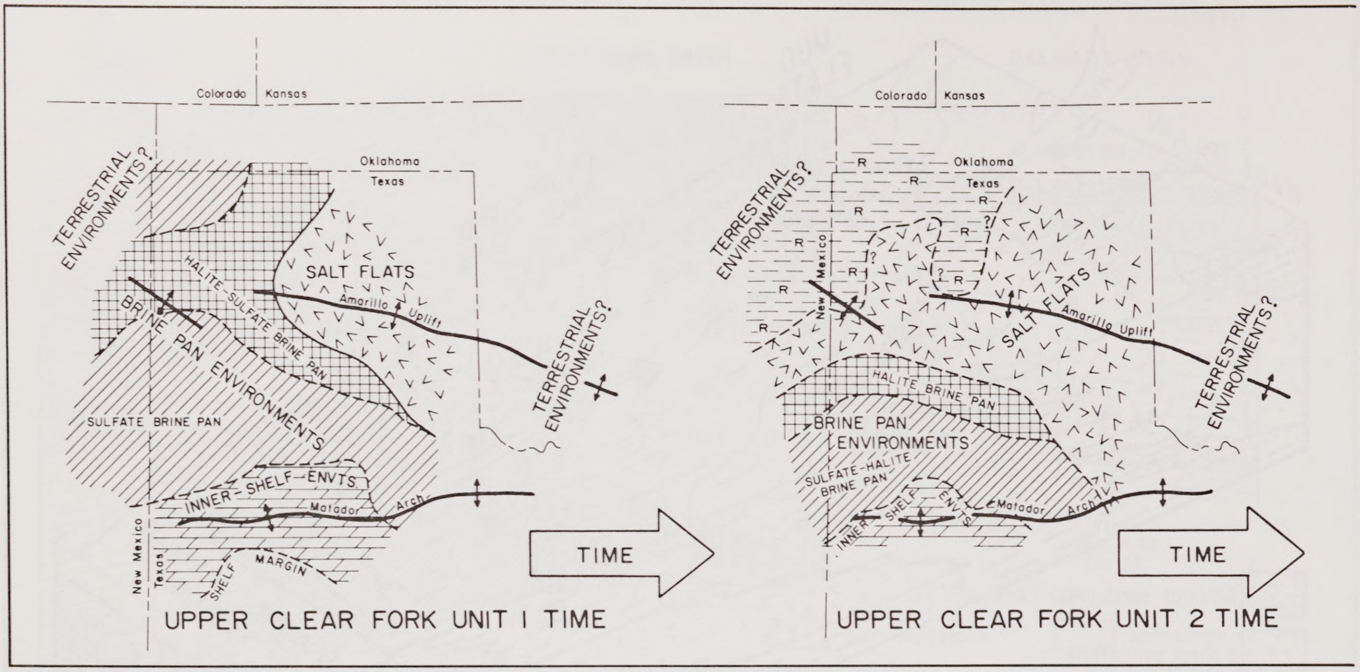


Figure 5. Paleogeography at the time of deposition of the upper Clear Fork and Glorieta Formations.

Table 1. Stratigraphic chart of Permian rocks in the Palo Duro and Dalhart Basins.

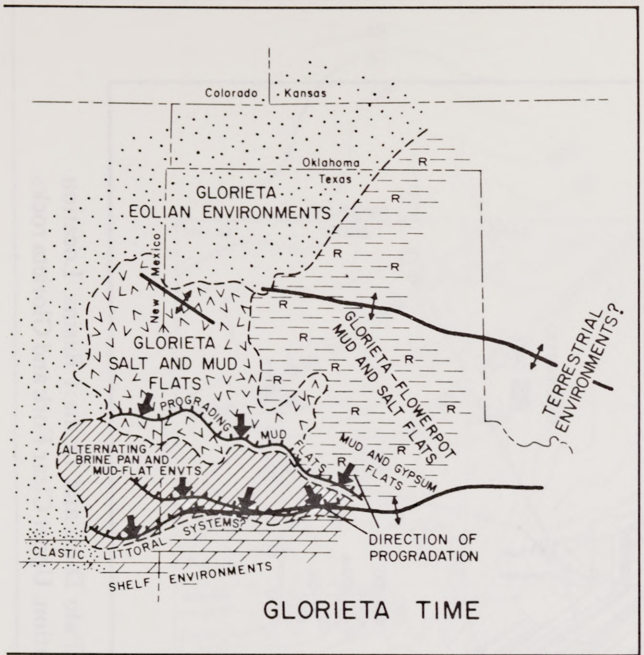
System	Series	Palo Duro Basin		Dalhart Basin	
PERMIAN	Ochoa	Post - San Andres Interval	Dewey Lake Formation	Post-Blaine Red Beds	Dewey Lake Formation
	Ochoa	Post - San Andres Interval	Alibates Formation	Post-Blaine Red Beds	Alibates Formation
	Guadalupe	Post - San Andres Interval	Salado Formation	Post-Blaine Red Beds	Undifferentiated
	Guadalupe	Post - San Andres Interval	Yates Formation	Post-Blaine Red Beds	Undifferentiated
	Guadalupe	Post - San Andres Interval	Seven Rivers Formation	Post-Blaine Red Beds	Undifferentiated
	Guadalupe	Post - San Andres Interval	Queen/Grayburg Formation	Post-Blaine Red Beds	Undifferentiated
	Guadalupe	San Andres Formation		Blaine Formation	
	Leonard	Clear Fork Group	Glorieta Formation	Glorieta Sandstone	
	Leonard	Clear Fork Group	upper Clear Fork Formation	Clear Fork Formation	
	Leonard	Clear Fork Group	Tubb Formation	Undifferentiated Tubb - Wichita Red Beds	
	Leonard	Clear Fork Group	lower Clear Fork Formation	Undifferentiated Tubb - Wichita Red Beds	
	Leonard	Clear Fork Group	Red Cave Formation	Undifferentiated Tubb - Wichita Red Beds	
	Leonard	Wichita Group			
	Wolf-camp				

The Glorieta Formation contains interbedded clastic and evaporite-carbonate units. Glorieta evaporites and carbonates grade southward from salt-dominant lithologies to anhydrite and dolomite. Glorieta clastic units are mostly mudstone-siltstone in the Palo Duro Basin. These grade to the south into sandy dolomites in the northern Midland Basin and to the northwest into laterally persistent Glorieta sheet sandstones.

In the study area, the combined upper Clear Fork and Glorieta Formations thicken to the southwest as much as 400 m (1,300 ft; fig. 7). Gustavson and others (1980a) have shown that marked thinning of upper Clear Fork-Glorieta rocks along the Amarillo Uplift is due to subsurface dissolution of Glorieta salt beds by ground water. In the Palo Duro Basin, the upper Clear Fork Formation is thickest in the basin center, whereas the Glorieta Formation thickens from northeast to southwest (figs. 11 and 12).

Stratigraphy

The upper Clear Fork and Glorieta Formations of the central Texas Panhandle are equivalent to the Clear Fork Formation and the lower part of the Glorieta Sandstone in the Dalhart Basin (table 1; fig. 8). Equivalent units in the Anadarko Basin are the upper Cimarron Salt and the Flowerpot Shale (Johnson and Gonzales, 1978; fig. 10). To avoid confusion in terminology, it is important to note that the name "Glorieta" has been used in the past for at least three distinct facies in the Texas Panhandle and eastern New Mexico (fig. 2): (1) the Glorieta Sandstone in



(Figure 5 continued.)

the Dalhart Basin and in northeastern New Mexico contains laterally persistent, tabular beds deposited in eolian environments and intertonguing with red muds and siltstones (Presley, 1981); (2) the Glorieta Formation in the central Texas Panhandle, of major interest in this report, contains red beds and salt; and (3) another "Glorieta Sandstone" in the southern Texas Panhandle and east-central New Mexico intertongues with carbonates and was deposited in nearshore and littoral marine environments (Milner, 1978).

In the Palo Duro Basin, the upper Clear Fork Formation is informally subdivided. The lower part of the upper Clear Fork Formation contains only minor red beds and is referred to as "unit 1"; the upper part of the upper Clear Fork Formation has more clastics and is named "unit 2" (figs. 8 and 9). Major cyclic alternations of carbonate and evaporite sediments observed in upper Clear Fork rocks are labeled, oldest to youngest, "cycles 1A, 1B, 2A, 2B, 2C, and 2D." Three clastic units in the Glorieta Formation are named, oldest to youngest, "units A, B, and C"; three evaporite-carbonate units interbedded with the Glorieta clastics are referred to as "units 1, 2, and 3" (figs. 8 and 9).

Previous Studies

Galley (1958), Nicholson (1960), and McKee and others (1967) have summarized regional stratigraphic and structural relationships. Johnson and Gonzales (1978) discussed the regional geology of salt-bearing strata in the Permian Basin. Dutton and others (1979) and Gustavson and others (1980b) reported on general aspects of the geology and geohydrology of the Palo Duro and Dalhart Basins. In the Dalhart and Anadarko regions, Cunningham (1961) described lithologic variations in Leonardian rocks. Jordan and Vosburg (1963) presented a detailed stratigraphic analysis of Permian evaporites in the Anadarko Basin.

Silver and Todd (1969) grouped Lower Permian rocks of the Texas Panhandle into a number of offlapping cyclic sequences. Upper Clear Fork rocks were grouped into a "shelf" evaporite and carbonate facies suite, whereas Glorieta equivalents were considered "shelf detrital facies," representing arid continental environments. Permian sabkha systems in Texas and New Mexico have been discussed by Handford (1980) and Jacka and Franco (1973). Jeary (1978) studied upper Clear Fork carbonate shelf facies in the northern Midland Basin. Early Permian geologic history before Clear Fork deposition was described by Handford (1979) and Handford and Dutton (1980).

Data

Geophysical logs, sample logs, and cores were used in this study. Well identification numbers on cross sections correspond to an index system at the Bureau of Economic Geology (table 2). Cores used in this study were from the DOE-Gruy No. 1 Rex H. White well in Randall County and from the DOE-Gruy No. 1 Grabbe well in Swisher County (figs. 13 and 14). Both cores were drilled by the U. S. Department of Energy and are continuous through the upper Clear Fork-Glorieta study interval. Geophysical logs of both wells provide the basis for correlation of log patterns with lithology. Many of these facies can be recognized in other wells in the basin. Log parameters defining facies in the test wells are listed in table 4. Individual facies are discussed in the text.

INNER-SHELF DEPOSITIONAL SYSTEMS

Thick upper Clear Fork and Glorieta carbonates in the southern Palo Duro Basin were deposited predominantly in inner-shelf marine environments and are composed of upward-shoaling cycles of limestone and dolomite (tables 3 and 4; figs. 2, 3, and 8). Wilson (1975) referred to these upward-shoaling successions as lime mud-sabkha cycles. In this study the inner-shelf depositional system is considered an environment in which carbonate intertidal and sabkha facies cyclically prograded across shelf deposits.

Inner-shelf depositional facies in upper Clear Fork-Glorieta rocks in the southern Palo Duro Basin were not observed in core in this study. In sample logs these rocks are commonly described as gray to light-brown to brown dolomite, finely crystalline and commonly slightly anhydritic.

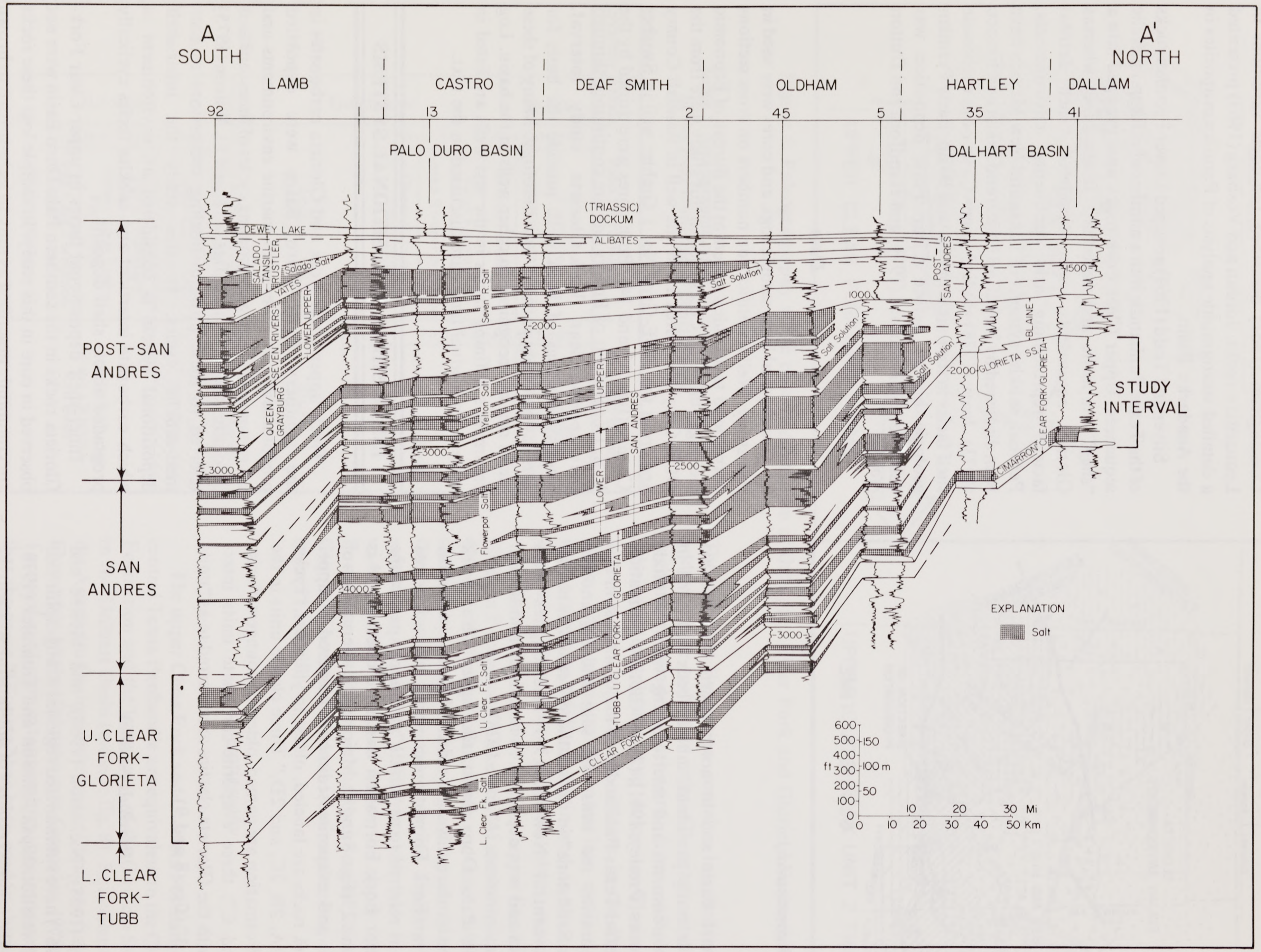


Figure 6. North-south cross section A-A′, Upper Permian salt-bearing formations, Palo Duro and Dalhart Basins. Location shown in figure 1. Generalized salt units are correlated. Datum is top of Alibates Formation. Upper Clear Fork and Glorieta rocks are in the lower part of section.

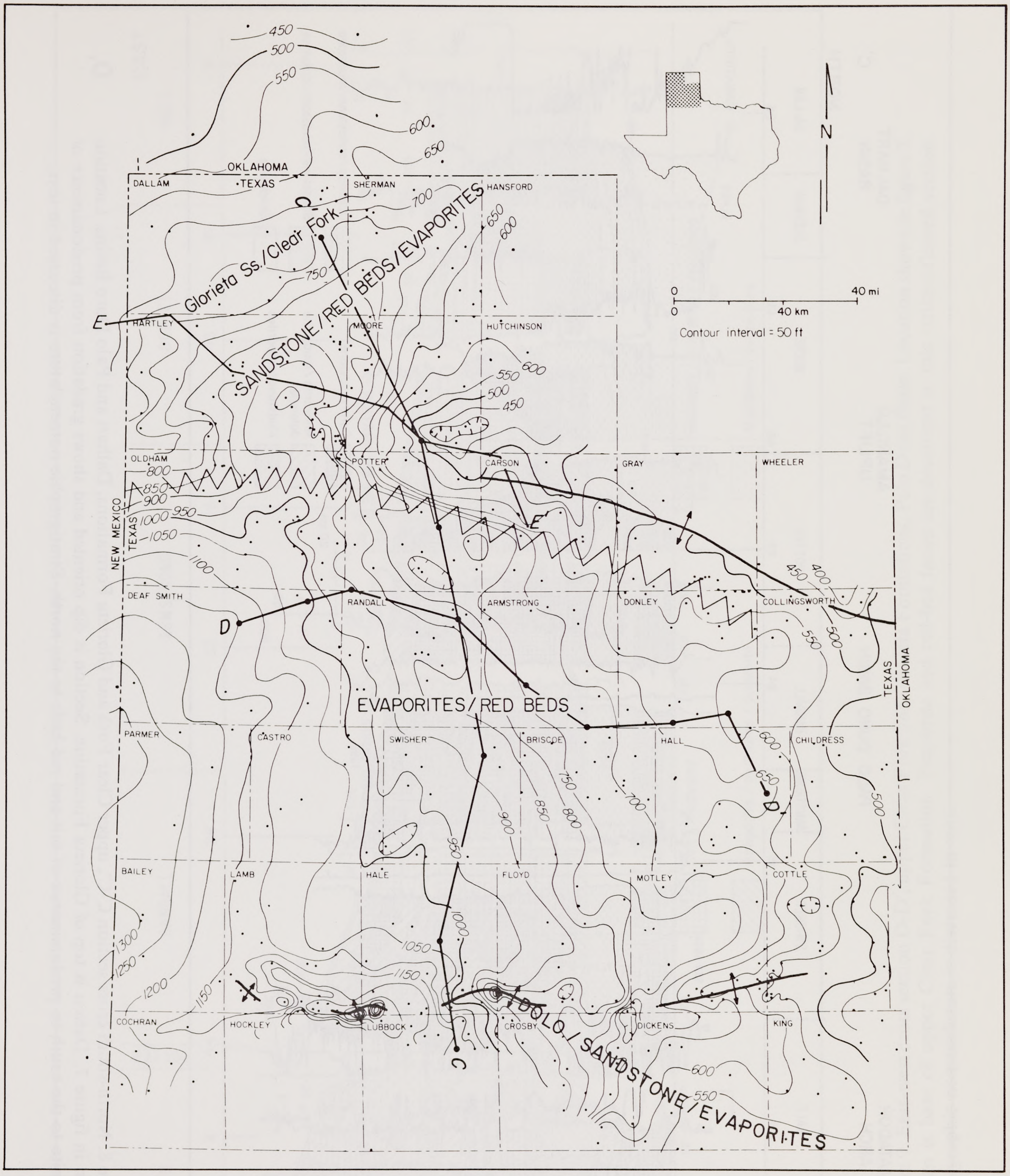


Figure 7. Isopach map of upper Clear Fork-Glorieta lithogenetic unit, Palo Duro and Dalhart Basins. Interval in Palo Duro Basin is composed of evaporites and red beds grading into dolomite to the south. Equivalent strata in Dalhart Basin compose Clear Fork red beds and evaporites and lower part of the Glorieta Sandstone. Nomenclature changes at position of serrate line. In general, study interval thickens from northeast to southwest. Along Matador Arch, movement of several individual fault blocks controlled sedimentation, as evidenced by abrupt changes in isopach patterns. Positions of uplifted blocks are positions of thinning. Along southern margin of Amarillo Uplift, abrupt thinning is partly due to subsurface dissolution of salt beds.

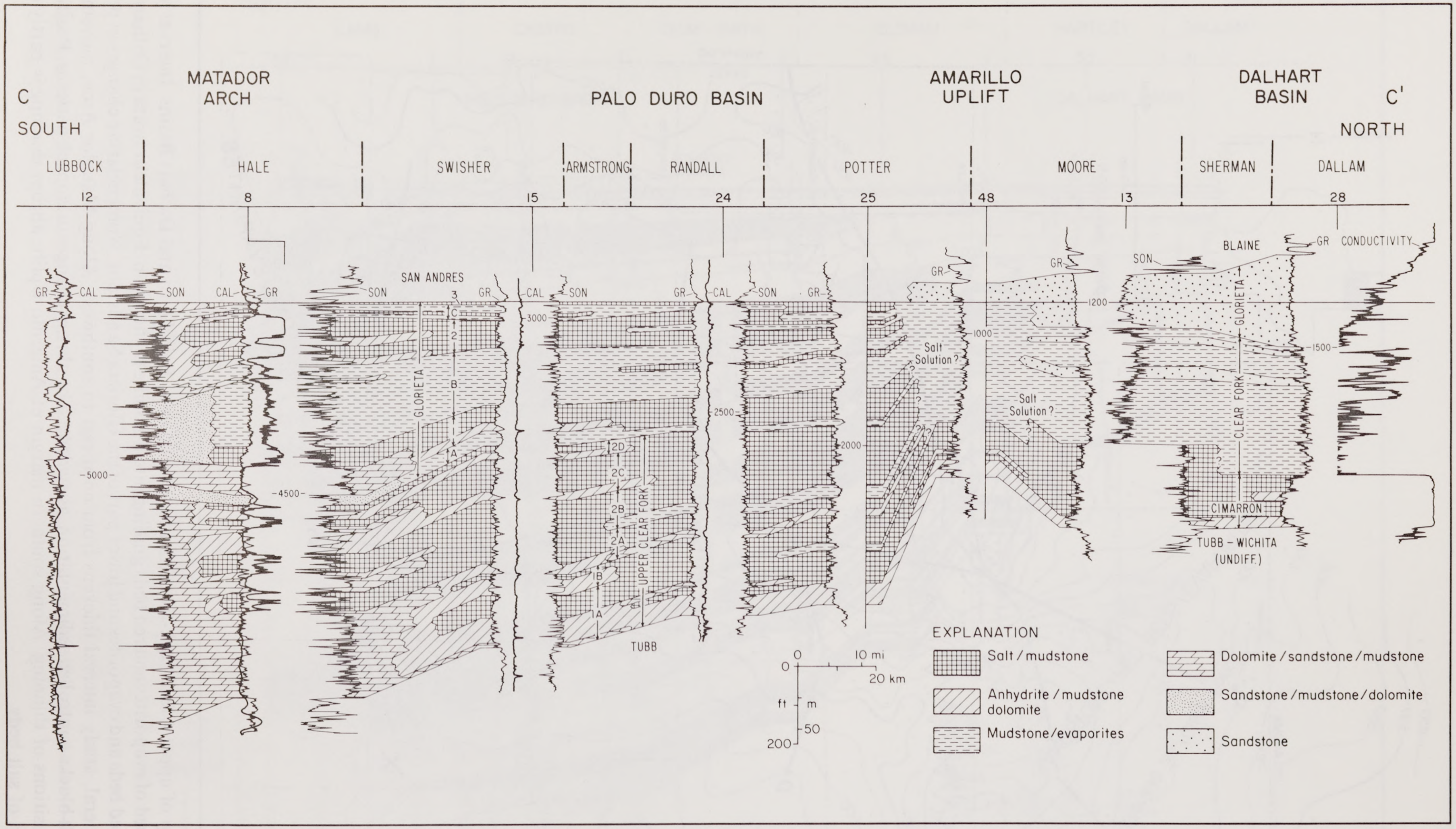


Figure 8. North-south cross section C-C′, upper Clear Fork and Glorieta Formations, Dalhart and Palo Duro Basins. Location shown in figure 7. Datum is top of Glorieta Formation. Section is dip oriented and shows gradation from predominance of dolomite to the south to predominance of salt and red beds to the north. Stratigraphic nomenclature is discussed in text.

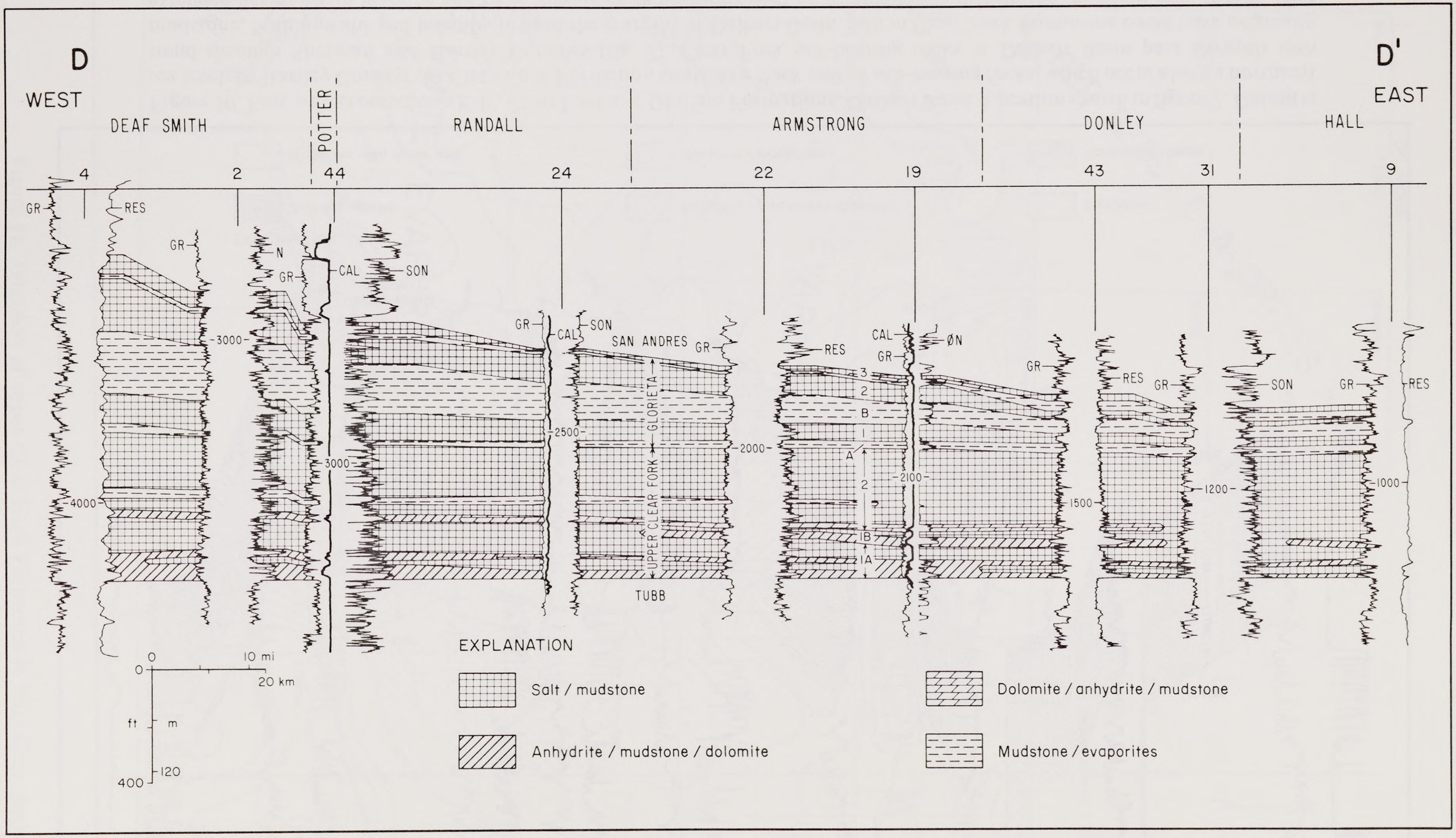


Figure 9. East-west cross section D-D′, upper Clear Fork and Glorieta Formations, Palo Duro Basin. Location shown in figure 7. Datum is base of upper Clear Fork Formation. Evaporite and red-bed facies are dominant in this strike-oriented section. Stratigraphic nomenclature is discussed in text.

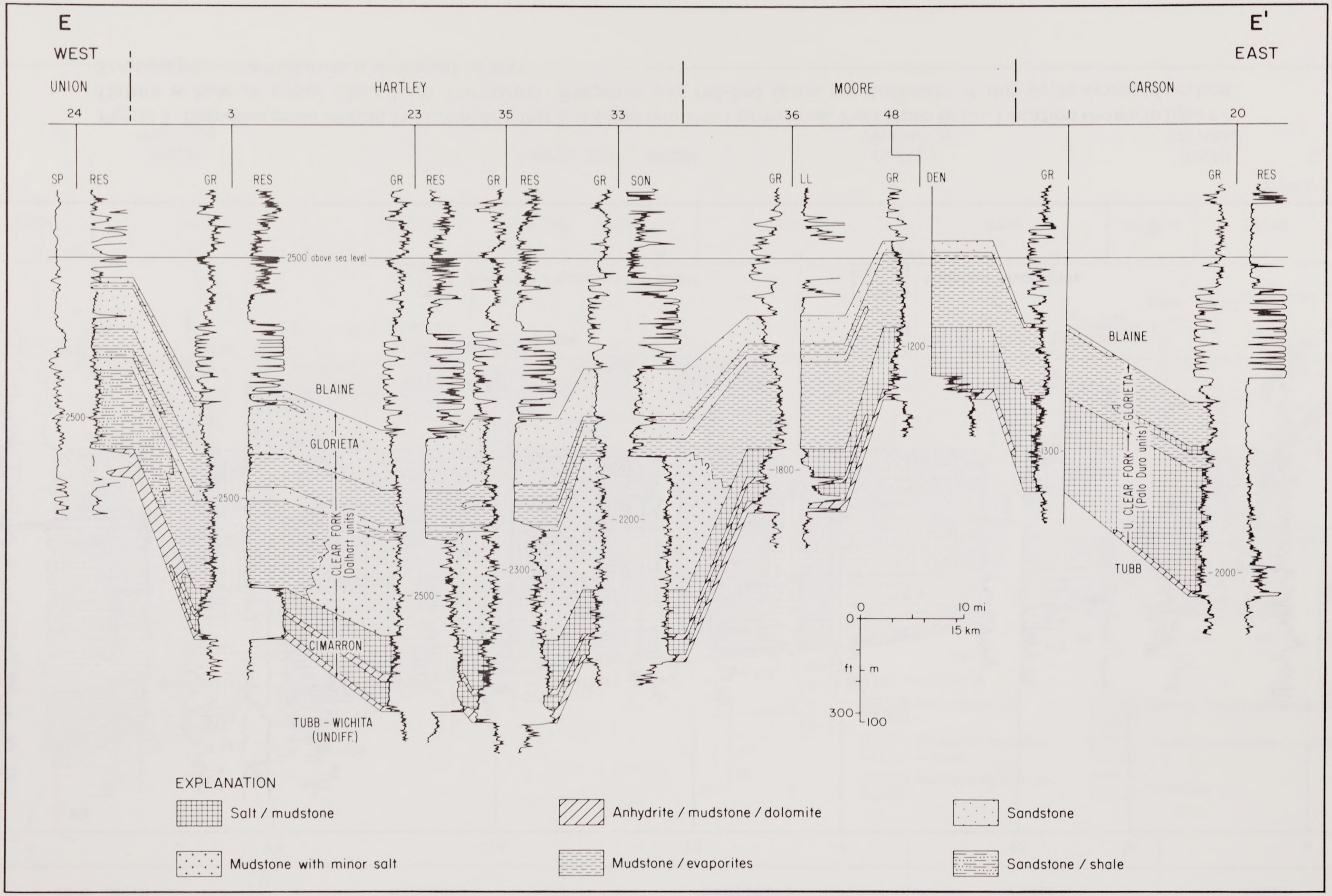


Figure 10. East-west cross section E-E′, Clear Fork and Glorieta Formations, Dalhart Basin. Location shown in figure 7. Datum is sea level. In Hartley County, the Clear Fork Formation contains a thick unit of salt-bearing rocks, which occur along a northeast trend through Sherman and Hartley Counties (fig. 7). Clear Fork salt-bearing rocks in Dalhart Basin pass abruptly into mudstone, both upward and laterally toward the margins of Dalhart Basin. Salt in Clear Fork Formation could have originally extended across basin margins and have subsequently been removed by ground-water dissolution, possibly only shortly after deposition. Or perhaps Dalhart Basin margins were relatively emergent during deposition of salt in the central part of basin, and no salt was deposited in marginal areas.

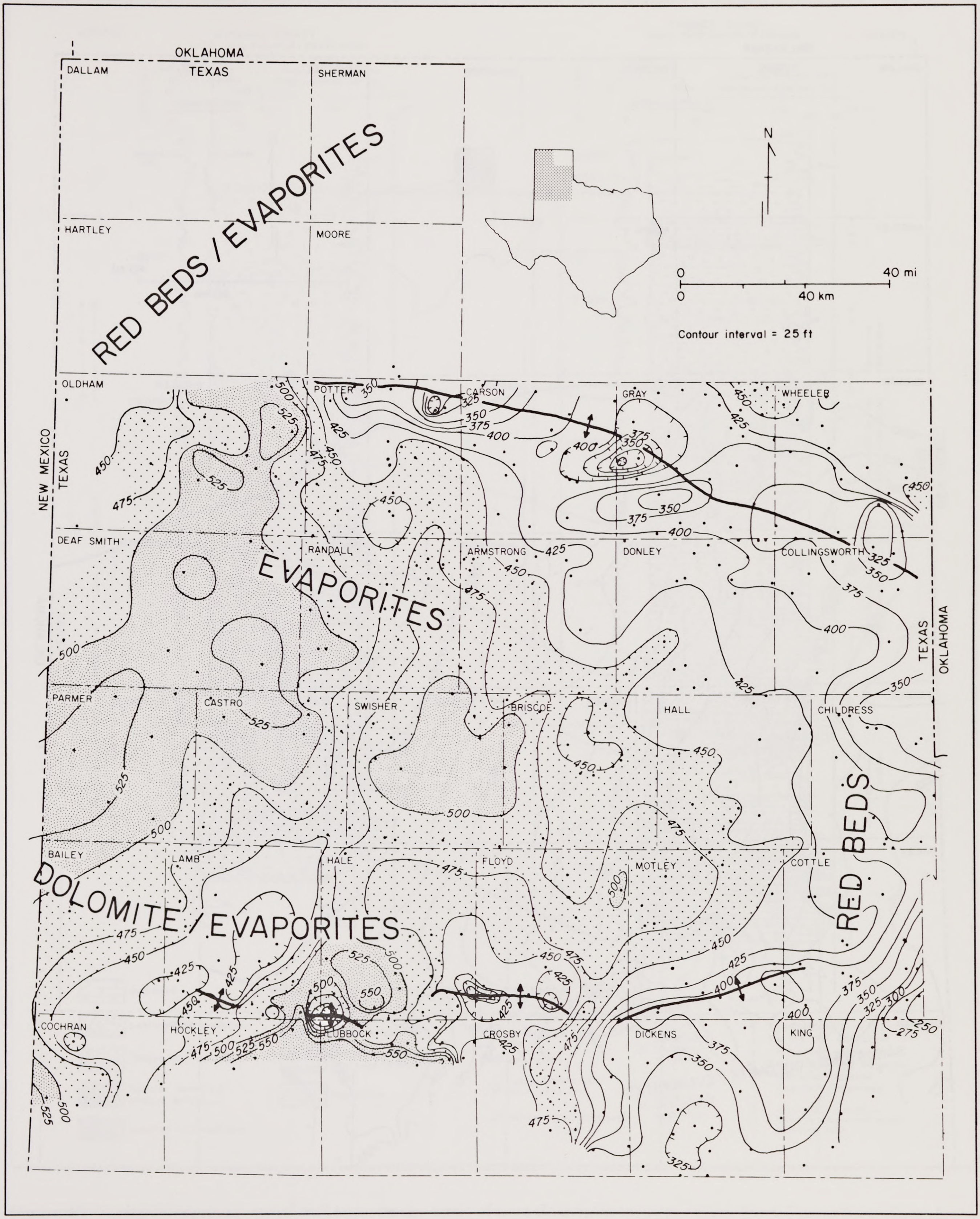


Figure 11. Thickness of upper Clear Fork Formation in Palo Duro Basin.

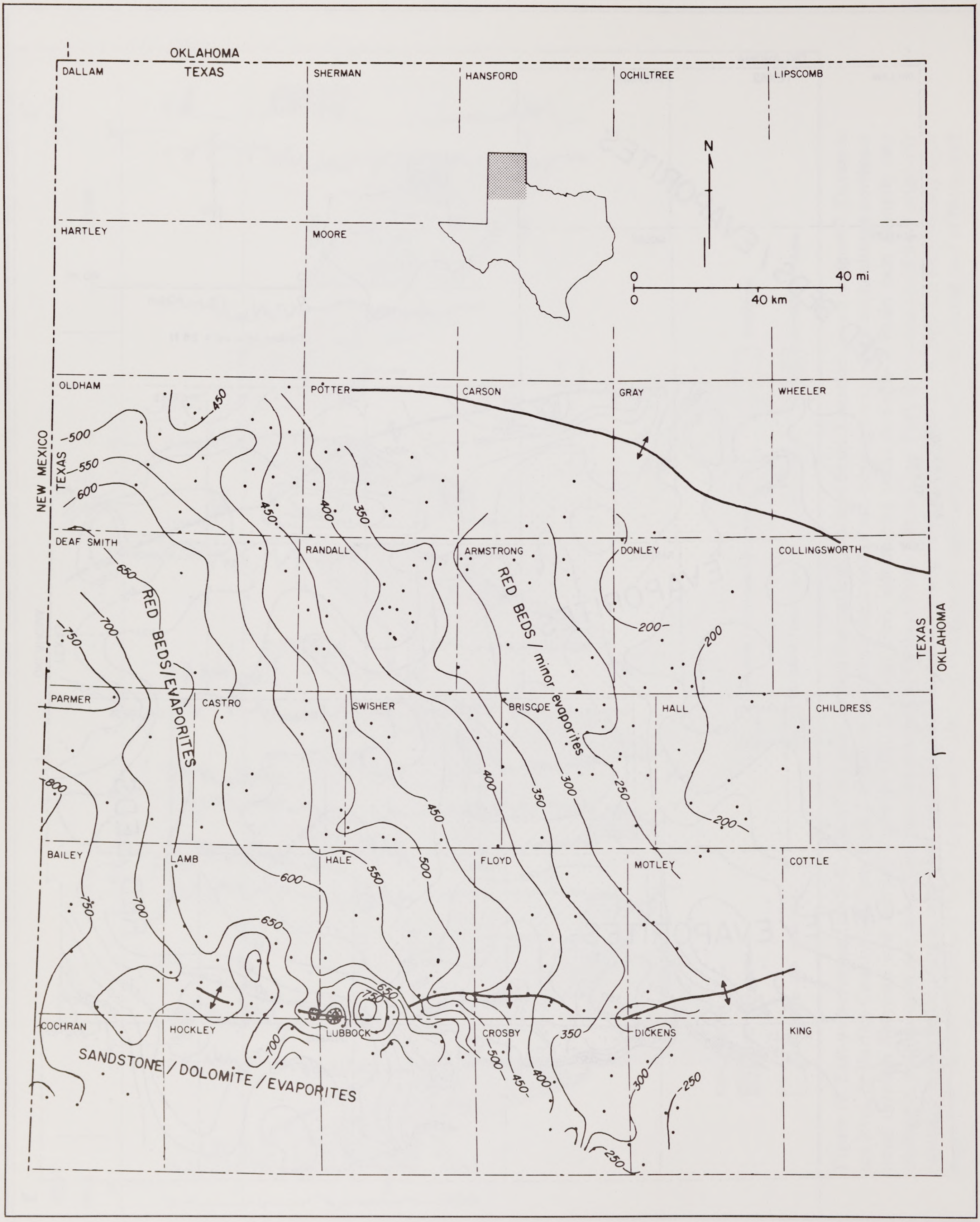


Figure 12. Thickness of Glorieta Formation in Palo Duro Basin.

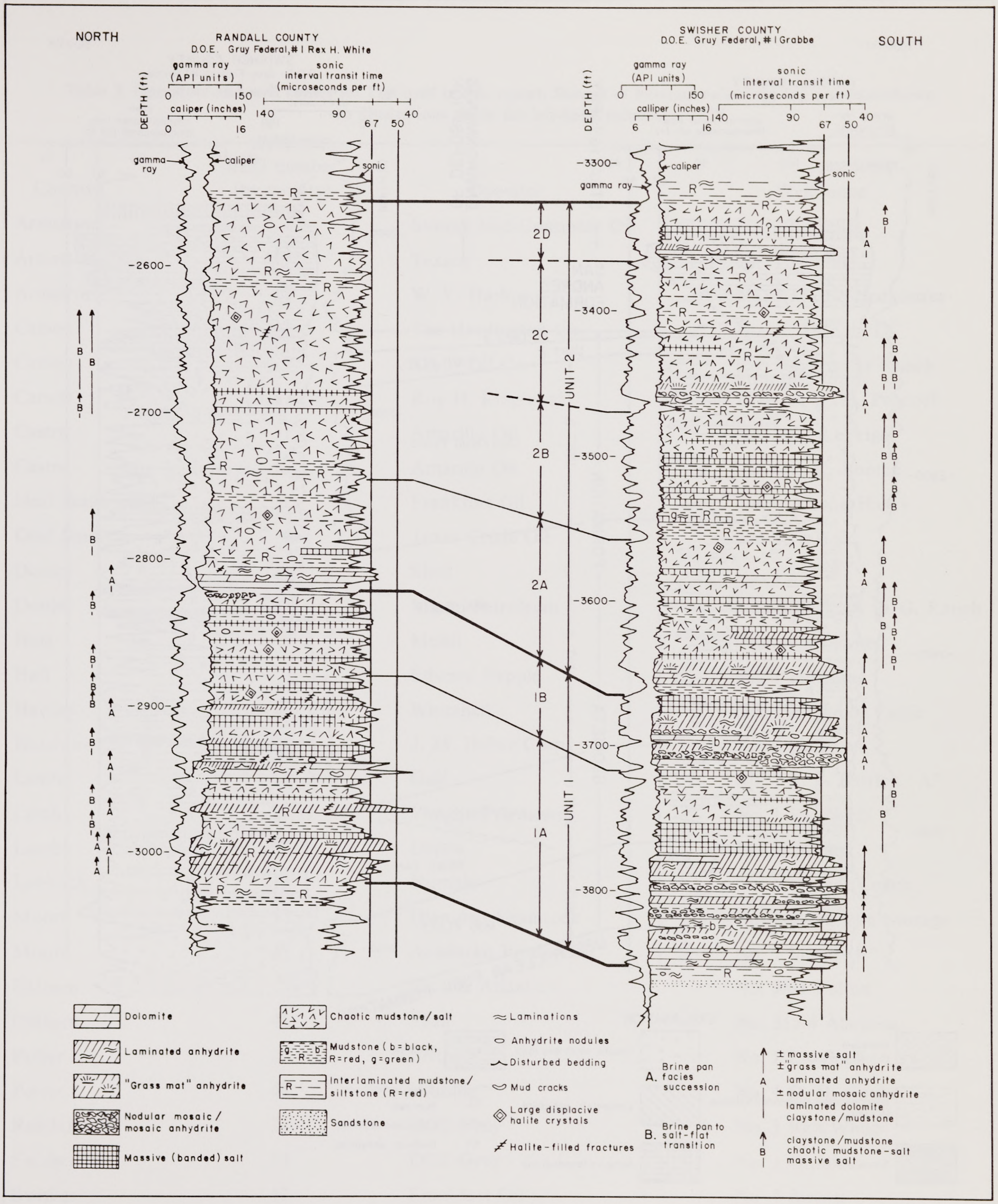


Figure 13. Facies interpretations of well logs, on the basis of core descriptions, upper Clear Fork Formation. Cores from wells were continuous through this interval. Core locations shown in figure 1. Salt facies grade upward and northward from relatively massive salt to chaotic mudstone-salt. Individual cycles exhibit similar gradation. Facies show consistent well log character, as described in table 4.

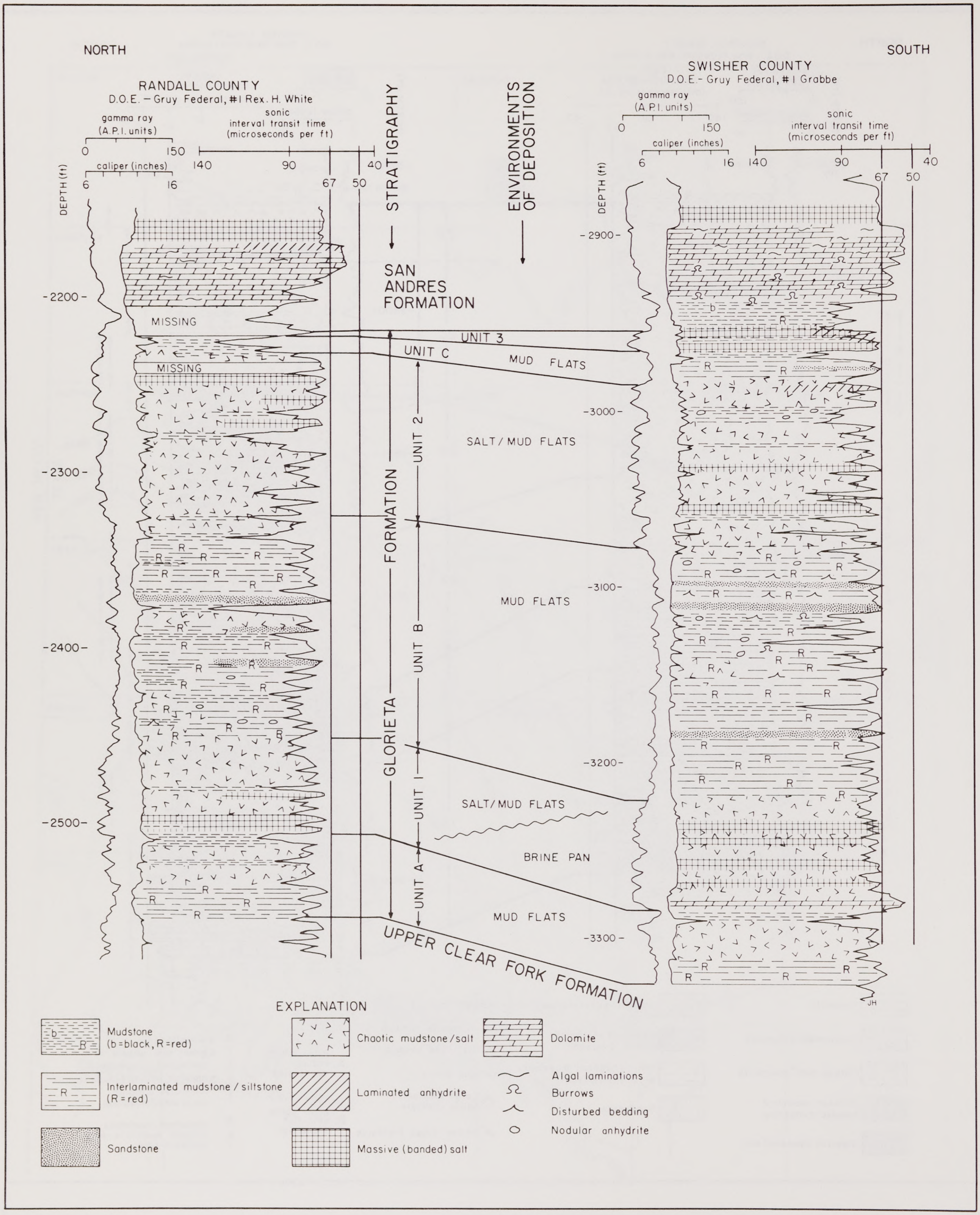


Figure 14. Facies interpretations of well logs, on the basis of core descriptions, Glorieta Formation. Core locations shown in figure 1.

Table 2. Operators and well names for logs used in this report. Bureau of Economic Geology log numbers shown on illustrations are in the left-hand column.

County	BEG number (by county)	Operator	Well name
Armstrong	4	Sunray Mid-Continent Oil	No. 1 Cope
Armstrong	19	Texaco	No. 1 Ritchie
Armstrong	22	W. V. Harlow	No. 1 Mattie Hedgecoke
Carson	1	The Headington Co.	No. 1 Sanford "D"
Carson	7	Skelly Oil Co.	No. 262 Schafer Ranch
Carson	33	Roy H. King et al.	F. M. & C. M. Peacock
Castro	1	Amarillo Oil	No. 1 C. R. Veigel
Castro	13	Amarillo Oil	No. 1 L. C. Boothe
Deaf Smith	2	Frankfort Oil	No. 1 Allison-Hayes
Deaf Smith	4	Texas Crude Oil	No. 1-78 Rose
Donley	31	Shell	No. 1 Finch
Donley	43	Miami Petroleum	No. 162-1 Lazy R. G. Ranch
Hale	8	Mobil	No. 1 Carl Laney
Hall	9	Edward Nepple	No. 1 Hutchins
Hartley	35	Whitehall	No. 1 Reynolds Cattle
Hutchinson	21	J. M. Huber Corp.	No. 5 Harrison
Lamb	1	Gulf	No. 1 L. E. Bartlett "A"
Lamb	27	Vaughn Petroleum	No. 1 Eva Wells
Lamb	92	Depco	No. 10 Young
Lubbock	12	Humble	No. 1 Bernice Coach
Moore	13	Diamond Shamrock	No. 1 Robertson Storage
Moore	48	Anadarko Production	No. 1 Sneed "E"
Oldham	5	Shell & Atlantic	No. 98-1 Fulton
Oldham	45	Shell	No. 315-4 Alamosa
Potter	25	Bivins	No. 1 LX Shell
Potter	44	Humble	No. 1 O. H. Gouldy
Randall	24	DOE-Gruy	No. 1 Rex White
Swisher	15	DOE-Gruy	No. 1 Grabbe
Swisher	12	Frankfort Oil	No. 1 Sweatt

Table 3. Depositional systems in upper Clear Fork and Glorieta Formations in the Texas Panhandle.

	INNER-SHELF SYSTEMS	BRINE PAN SYSTEMS: OUTER BRINE PAN	BRINE PAN SYSTEMS: INNER BRINE PAN	SALT-FLAT SYSTEMS	MUD-FLAT SYSTEMS
DEPOSITIONAL SYSTEM	INNER-SHELF SYSTEMS	OUTER BRINE PAN	INNER BRINE PAN	SALT-FLAT SYSTEMS	MUD-FLAT SYSTEMS
ALTERNATE TERMINOLOGY	Lime mud-sabkha systems	Halite-sulfate brine pan	Halite brine pan	Salt-mud flats; mud-salt flats; inner salt plain	Mud-rich tidal flats
ENVIRONMENTAL SETTING	Prograding algal-flat environments; shallow-subtidal (low-energy), inter-tidal, and supratidal (sabkha) carbonate environments	Shallow-water hypersaline, supratidal ponds and lakes; ponding controlled to great extent by ground-water levels; salinity balance maintained by interaction of (a) ground-water and surface-water systems, (b) surface-water evaporation, and (c) precipitation/dissolution of salts		Supratidal, low-relief flats that may be periodically flooded, but are relatively exposed compared with brine pans; surface may be salt encrusted; precipitation interstitial in muds and previously deposited evaporites	Low-relief, mud-rich, coastal flats; environment intertidal to terrestrial; active processes may include wind-tidal flooding, and eolian deflation and sedi-mentation controlled by ground-water position
LITHOFACIES	Burrowed and churned dolomitic wackestones and packstones (subtidal to intertidal); algal-laminated dolomitic mudstones, commonly with desiccation structures and nodular anhydrite (intertidal to supratidal)	Laminated anhydrite, commonly with vertically arrayed gypsum pseudo-morphs ("grass mats"), and nodular-mosaic-anhydrite that disrupts laminae; relatively mud-free salt, typically banded; algal-laminated dolomitic mudstones	Relatively mud-free salt, typically banded; red mudstone	Mudstone and salt in chaotic mixtures, from mudstone with scattered halite crystals to crystalline salt with intercrystalline mud	Red mudstone and siltstone; mudstone beds typically structureless; mudstone and siltstone commonly inter-laminated; silt-rich laminae (± sand) commonly cross-laminated; adhesion-ripple structures present

Lucia (1972) described a range of subtidal to supratidal facies in cores of these inner-shelf systems in Clear Fork-age carbonates in the northwestern Midland Basin (table 5). According to Lucia, highly burrowed and churned dolomites record deposition in marine environments. Intertidal facies include carbonates with distinct burrows, algal structures, wispy laminations, current structures, and thin quartz silt beds, whereas supratidal facies include dolomite with wispy to irregular laminations, lithoclasts, desiccation features, and quartz silt beds.

BRINE PAN DEPOSITIONAL SYSTEMS

Landward of inner-shelf environments, evaporites as well as carbonates were deposited on a vast, low-relief supratidal surface. Southern parts of this evaporitic plain were commonly flooded with brines from periodic storm tides (wind-driven), spring tides, or ground water. A supply of water from terrestrial sources was possible. Those parts of the evaporitic plain that commonly contained standing water are referred to as brine pan environments (tables 3 and 4; figs. 2 and 3).

A characteristic succession of facies deposited in brine pans is visible in upper Clear Fork rocks from the Swisher and Randall cores (fig. 13). Inner-shelf facies in Clear Fork-Glorieta rocks are predominantly south of these core localities. The succession of brine pan facies that are observed in core is (1) laminated dolomite, grading upward into (2) nodular mosaic anhydrite, (3) laminated anhydrite, (4) "grass mat" anhydrite, which is a laminated anhydrite rock with halite-filled molds of vertically arrayed gypsum crystals, and (5) relatively massive salt deposits.

Laminated Dolomite

Dolomite observed in core of upper Clear Fork rocks from the central and northern Palo Duro Basin is typically laminated, dolomitic mudstone (fig. 15A). Dolomite beds are generally less than 3 m (10 ft) thick and are interbedded with anhydrite (figs. 13, 14, and 15). Laminations are considered algal in origin, are dark gray to black, and may be planar and smooth or wavy.

Dolomite observed in core is most abundant in the lower part of the upper Clear Fork Formation, particularly in the Swisher County core (fig. 13). These laminated dolomites are generally underlain by soft, dark shale and grade upward into beds of nodular mosaic or laminated anhydrite.

This succession is somewhat similar to facies deposited in modern hypersaline lakes on the coast of the Caribbean island of Bonaire (Deffeyes and others, 1965; Lucia, 1968). Recent sediments beneath these hypersaline lakes are a succession of carbonates and gypsum (Lucia, 1968; fig. 16). At the base of this sequence are relatively open marine carbonates overlain by a volcanic ash bed, which is a partial aquitard for circulating marine ground waters and allows high salinities to develop in surface waters. Sediments overlying the ash bed are composed of pelleted lime mud overlain by bedded gypsum. The lime mud is exposed on algal-mat-covered supratidal flats adjacent to the hypersaline lakes. Gypsum overlying the lime mud is deposited in the lakes and is characteristically

Table 4. Carbonate-evaporite facies of upper Clear Fork-Glorieta rocks, based on core descriptions and well log patterns.

← INNER SHELF		BRINE PAN		SALT FLATS
Core descriptions	Laminated dolomite	Laminated or nodular mosaic anhydrite	Massive-banded salt	Chaotic mudstone-salt
Lithology and color	Tan to dark-gray-green dolomite-mudstone. Commonly with gray anhydrite laminae and nodules. Halite is common, filling fractures and porosity.	Bluish-gray, laminated or nodular mosaic anhydrite.	Clear halite, commonly appears red-brown with red mudstone impurities.	Clear halite and red-brown mudstone. Mixtures vary from crystalline salt with intercrystalline mudstone to predominantly mudstone with a few scattered salt crystals.
Bed-laminae dimensions	Dolomite occurs in beds up to 10 ft (3 m) thick. Individual dolomite laminae are up to 0.5 inch (1.3 cm) thick; anhydrite stringers are up to 0.25 inch (0.6 cm) thick; beds of nodules are 0.5 to 1.0 inch (1.3 to 2.5 cm) thick.	Occurs in beds up to 10 ft (3 m) thick. Laminae are up to 0.2 inch (0.5 cm) thick, and are commonly separated by thin carbonate/organic films.	Massive salt beds up to 10 ft (3 m) thick are commonly banded into layers 1 to 6 inches (2.5 to 15 cm) thick by variation in percentage of red mudstone and other impurities. Intervals of relatively pure salt are up to 3 ft (1 m) thick. Some anhydrite is present as thin (0.1 inch, 0.25 cm) stringers.	Chaotic mudstone-salt beds are commonly on the order of 1 to 20 ft (0.3 to 6 m) thick.
Textural relationships	Anhydrite nodules commonly distorted, elongate parallel to bedding. Individual nodules are less than 0.5 inch (1.3 cm) in average diameter.	Upper surfaces of laminated anyhydrite may exhibit dovetail anhydrite crystals as pseudomorphs after gypsum, extending upward, commonly into salt. Some laminae exhibit wavy bedding or enterolithic deformation. Anhydrite nodules average 0.5 to 1 inch (1.3 to 2.5 cm) in diameter. Nodules may be equidimensional or elongate parallel to bedding, and are separated by carbonate/organic films.	Salt crystal size commonly 0.5 to 1.0 inch (1.3 to 2.5 cm) in diameter with crystals up to 2 inches (5 cm) in diameter. Crystals generally equant, anhedral.	Salt crystals are up to 1.5 inch (3.8 cm) in diameter but are most commonly 0.25 to 0.5 inch (0.6 to 1.3 cm). Salt and mudstone appear randomly intermixed. Salt crystals are generally equant and anhedral. Subhedral to euhedral crystal boundaries are common where salt contacts mud.
Well log patterns	Dolomite facies register moderate radioactivity (20 to 60 API units) as recorded on gamma-ray logs. Values on sonic logs average 60 to 70 microseconds. Higher percentages of anhydrite result in lower radioactivity and lower values of transit time.	Uniform, low radioactivity (average less than 15 API units) on gamma-ray logs. Interval transit time 50 to 60 microseconds on sonic logs; "cleanest" anhydrite approaches 50 microseconds.	Low radioactivity (5 to 15 API units) on gamma-ray logs. Interval transit time 67 to 70 microseconds.	Radioactivity is directly proportional to mudstone content. Gamma-ray values 15 to 45 API units. Sonic travel times average 60 to 90 microseconds. Travel time values greater with increasing mudstone.

Table 5. Sequence of sedimentary features in upper Clear Fork Formation, Flanagan Field, Texas (from Lucia, 1972).

Interpreted sedimentary environment	Sedimentary structure	Fossils	Particle size
Supratidal	Irregular laminations, lithoclasts, desiccation features, quartz silt beds	*Rare* Thin-shelled small foraminifers, ostracods, mollusks	Lithoclasts to lime mud
Intertidal	Distinct burrows, churned- to wispy-mottled structures. Quartz silt beds. Algal stromatolites. Discontinuous fractures.	*Very few* Thin-shelled small foraminifers, ostracods, mollusks, filamentous algae	Fine sand-sized pellets to lime mud
(channel)	Current-laminated rocks, crossbedding	*Very few* Echinoids, small mollusks	Fine sand-sized pellets to mud with some lithoclasts
Marine	Churned rocks, burrowed rocks	*Locally abundant* Echinoids, large fusulinids, mollusks, algae (?) foraminifers (?), bryozoans	Coarse sand-sized pellets to lime mud

laminated; the laminae are composed of prismatic gypsum crystals 0.1 to 12 mm (0.004 to 0.47 inch) long (Lucia, 1968).

Following a Bonaire analogy, the succession in upper Clear Fork-Glorieta rocks, from laminated carbonates grading upward to laminated anhydrite (± nodular mosaic anhydrite), is considered a record of gradual submergence of supratidal carbonate flats beneath brine pan waters and subsequent burial of carbonates by gypsum deposited in the brine pans.

The general lack of burrowing and bioclastic debris within upper Clear Fork-Glorieta laminated carbonates, as observed in cores, seems to preclude subtidal environments. Subtidal-supratidal carbonate facies couplets, as described by Lucia (1972; table 5) in upper Clear Fork inner-shelf depositional systems in the northern Midland Basin, were not observed in upper Clear Fork cores in the central and northern Palo Duro Basin. The laminated supratidal sediments in these Palo Duro cores probably intertongue to the south with increasingly intertidal and subtidal facies.

Nodular Mosaic Anhydrite

Beds of nodular mosaic anhydrite overlie a number of laminated dolomite beds observed in core. The term "nodular mosaic anhydrite" follows the terminology of Maiklem and others (1969). Anhydrite nodules average 1.3 to 2.5 cm (0.5 to 1 inch) in diameter (fig. 15B). Nodules may be equidimensional or elongate parallel to bedding and are commonly separated by partings of carbonate, clay, and organics. Where partings are absent, the term "mosaic" anhydrite is preferable (Maiklem and others, 1969).

Nodular mosaic beds may be sabkha facies similar to those observed on the Trucial Coast and in the Lower Purbeck of Great Britain by Shearman (1966), as well as in Devonian Elk Point evaporites of Alberta by Bebout and Maiklem (1973). However, within upper Clear Fork strata, nodular anhydrite growth fabrics are largely within discrete, thick-bedded units containing only a small proportion of dolomite. Complex displacive growth structures of anhydrite are uncommon within the laminated carbonates. The carbonate laminae are typically not disrupted by nodule growth or enterolithically folded anhydrite bands. Some of the nodular mosaic anhydrite may indeed be a sabkha sediment, but commonly, nodular mosaics grade into laminated anhydrite and may be a near-surface deformation texture of the laminated anhydrite. Perhaps the nodular beds formed by deformation of previously deposited bedded gypsum on brine pan margins that were periodically exposed. We are not aware of analogous occurrences. That the nodular mosaics are a replacement texture, as suggested by Bebout and Maiklem (1973) for similar rocks in

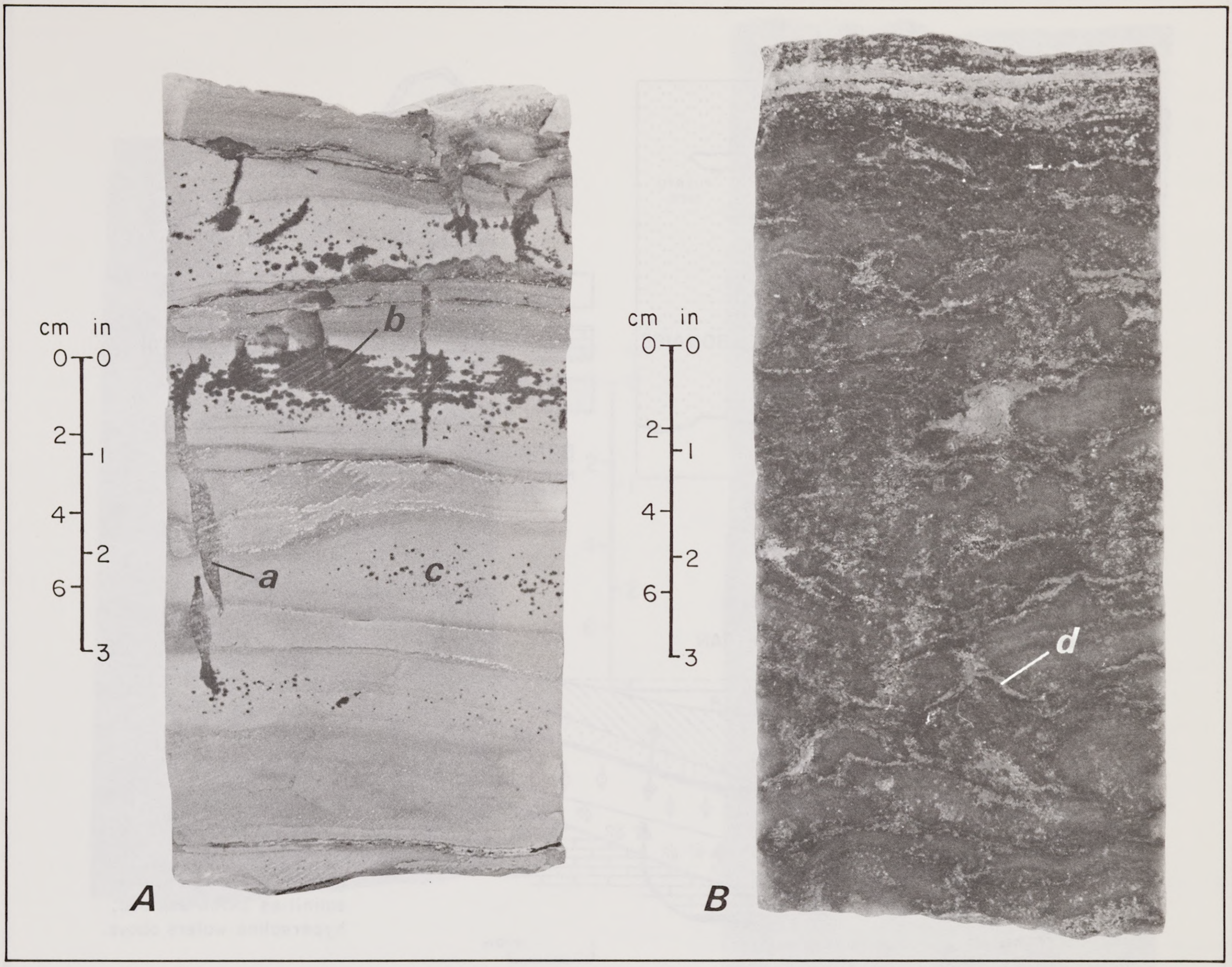


Figure 15. Dolomite and anhydrite facies from upper Clear Fork Formation. (A) Algal-laminated dolomite; halite filling fractures at (a); nodular anhydrite at (b); halite in carbonate mudstone at (c); from DOE-Gruy No. 1 Rex H. White, depth 898.2 m (2,947 ft). (B) Nodular mosaic anhydrite; lighter colored breaks between nodules (d) composed of dolomitic mudstone or anhydrite laths in halite matrix; internal texture of nodules is randomly oriented felted crystals (terminology of Maiklem and others, 1969); from DOE-Gruy No. 1 Grabbe, depth 1,168.6 m (3,834 ft).

Alberta, is considered unlikely since the nodular mosaic beds occupy a distinct recurring position in upper Clear Fork dolomite-to-anhydrite facies successions and thus appear to be facies controlled.

Laminated Anhydrite

Laminated anhydrite is commonly bluish gray. Laminae are up to 0.5 cm (0.2 inch) thick and are commonly separated by thin carbonate- or organic-rich films (fig. 17). Laminae are commonly slightly undulating and tend to pinch and swell. This facies occurs in beds up to 3 m (10 ft) thick (fig. 13). Both modern and ancient evidence suggests that these sediments are algal-bound storm deposits of clastic sulfates or direct gypsum precipitates on and within algal mats from ponded waters. The analogy of these laminated sulfates to bedded gypsum on the coast of Bonaire has been discussed (fig. 16).

Kendall (1978) considered such sulfate laminations, particularly those associated with evidence of current deposition, to be storm deposits on evaporitic tidal flats. According to Kendall, gypsum grains that were reworked into this sediment were derived from crystalline crusts on the sediment surface, which were easily broken in higher energy waters, or are acicular crystals precipitated at the air-water interface. Following storm activity, the gypsum layers were bound by blue-green algal mats. However, Kendall noted that detailed reconstruction of original environments from these laminated rocks is extremely difficult once the original gypsum fabric is lost during alteration of the sulfates to anhydrite.

Laminated anhydrite in upper Clear Fork-Glorieta rocks is similar to the balatino gypsum described by

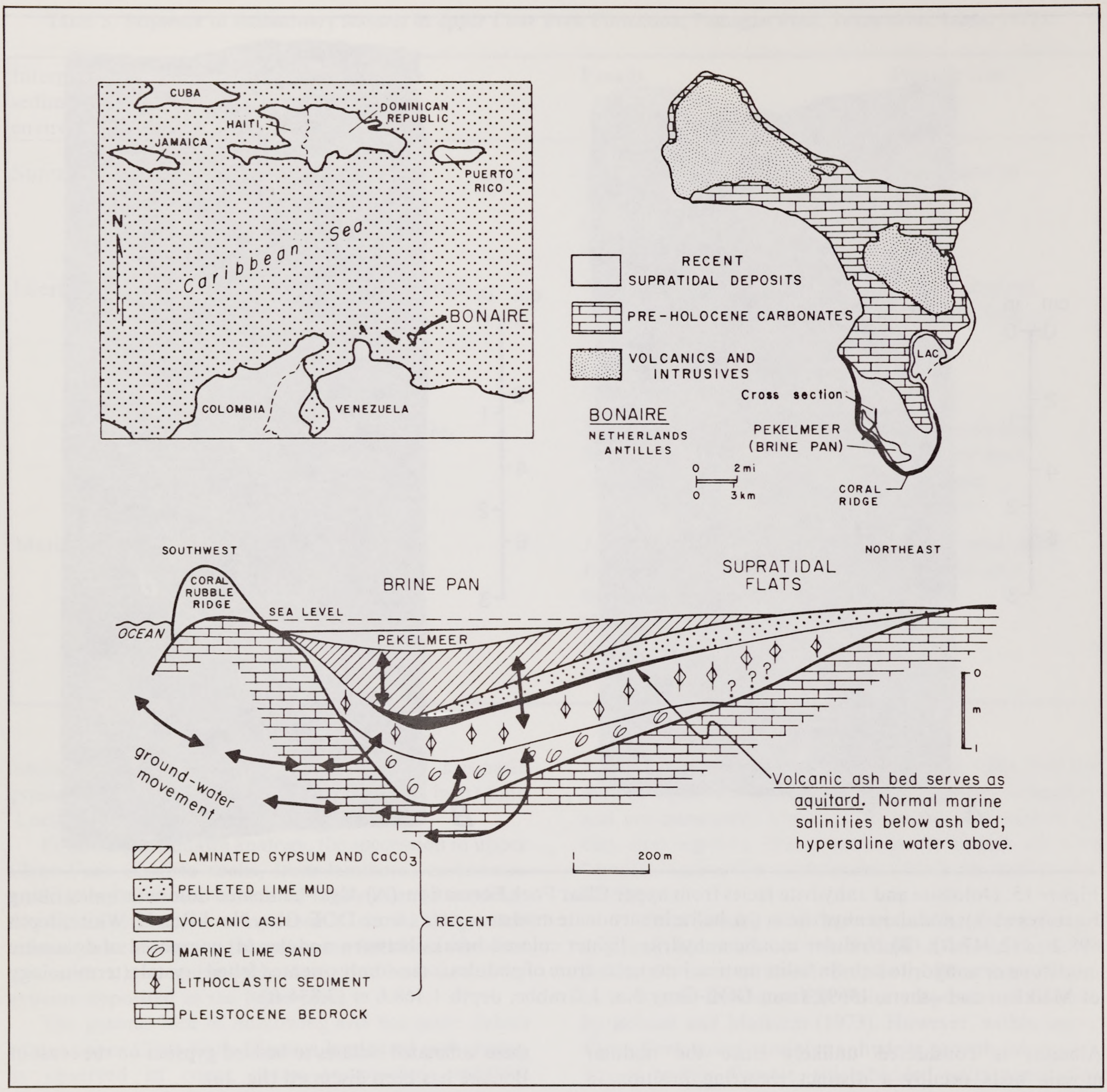


Figure 16. Carbonate and evaporite environments on southern coast of Caribbean island of Bonaire. Redrawn and modified from Lucia (1968) and Murray (1969).

Hardie and Eugster (1971) in Miocene evaporites of Sicily. Balatino gypsum laminations are parallel but have a pinch-and-swell structure. Gypsum layers are 1 to 3 mm (0.04 to 0.12 inch) thick, and wavy carbonate partings between the gypsum layers are up to 1 mm (0.04 inch) thick. Commonly the layers consist of granular gypsum, which Hardie and Eugster interpreted to be mechanically deposited storm layers of detrital gypsum. Some laminated sugar-textured gypsum in these Miocene evaporites has marked undulating laminae that drape over large isolated selenite crystals. Hardie and Eugster interpreted these to be algal stromatolites.

We have observed layered gypsum-crystal mush beneath the algal mat at Salina Ometapec, located on coastal mud flats adjacent to the Colorado River delta, near San Felipe, Baja California, Mexico (fig. 18). The gypsum appears to have grown in situ beneath the mat. Salina Ometapec, which is a supratidal brine pan, was flooded from spring tides at the time of our observation. The algal mat increased in thickness from shoreline areas

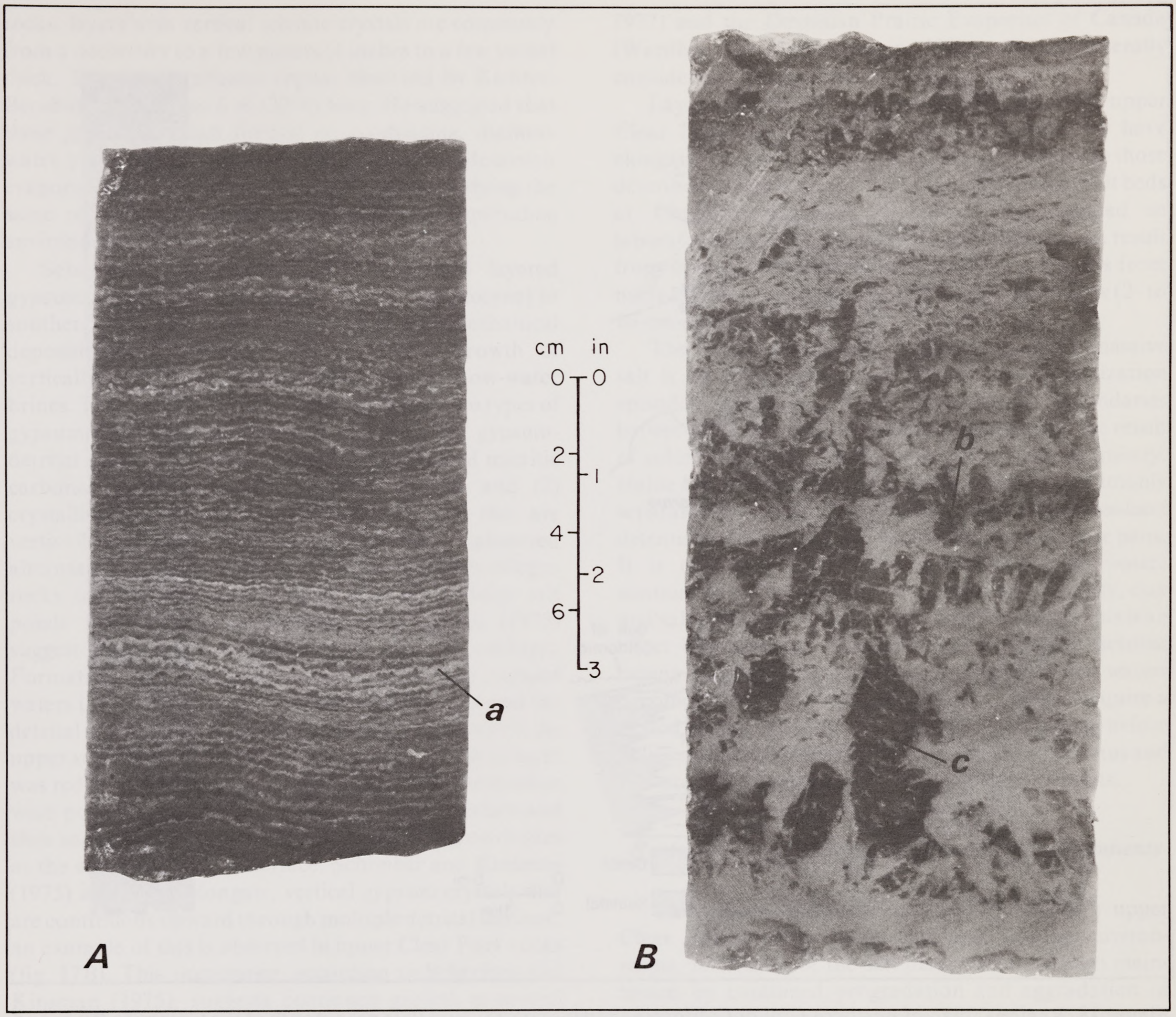


Figure 17. Anhydrite facies from upper Clear Fork Formation. (A) Laminated anhydrite; light-colored, crenulated laminae (a) are dolomitic mudstone; darker laminations are anhydrite; from DOE-Gruy No. 1 Grabbe, depth 1,111.0 m (3,645 ft). (B) "Grass mat" anhydrite; darker mineral is halite (b) replacing or filling molds of gypsum crystals; laminations crossing large gypsum pseudomorph (c) suggest periodic disruptions in brine salinity during crystallization; from DOE-Gruy No. 1 Rex H. White, depth 913.2 m (2,996 ft).

toward pan center. At the shoreline, the mat was crinkled; the crinkles were small linear folds up to 2 cm (0.8 inch) high in the wet mat surface. Sediment beneath the mat contained abundant small gypsum crystals, and crinkles were filled with a brownish-white, gypsum-crystal mush.

"Grass Mat" Anhydrite

Some laminated anhydrite observed in Palo Duro Basin cores exhibits crosscutting pseudomorphs of gypsum crystals that extend upward from laminae surfaces (fig. 17B). These pseudomorphs are filled or replaced by halite. Multiple layers of vertically arrayed pseudomorphs resemble stacked mats of coarse-textured turf, and the facies is termed "grass mat" anhydrite. The term "grass mats" is descriptive only and does not imply genesis. Kendall (1978) discussed possible environmental settings for "grass mat" gypsum facies and suggested that they formed in shallow-water hypersaline environments. Studies of other ancient examples of "grass mat" facies coincide with Kendall's (1978). Development of upper Clear Fork-Glorieta "grass mat" crystals in laminated sulfate facies may record prolonged brine pan flooding relative to other sulfate and carbonate deposits. If this is true, then the succession of brine pan facies observed in

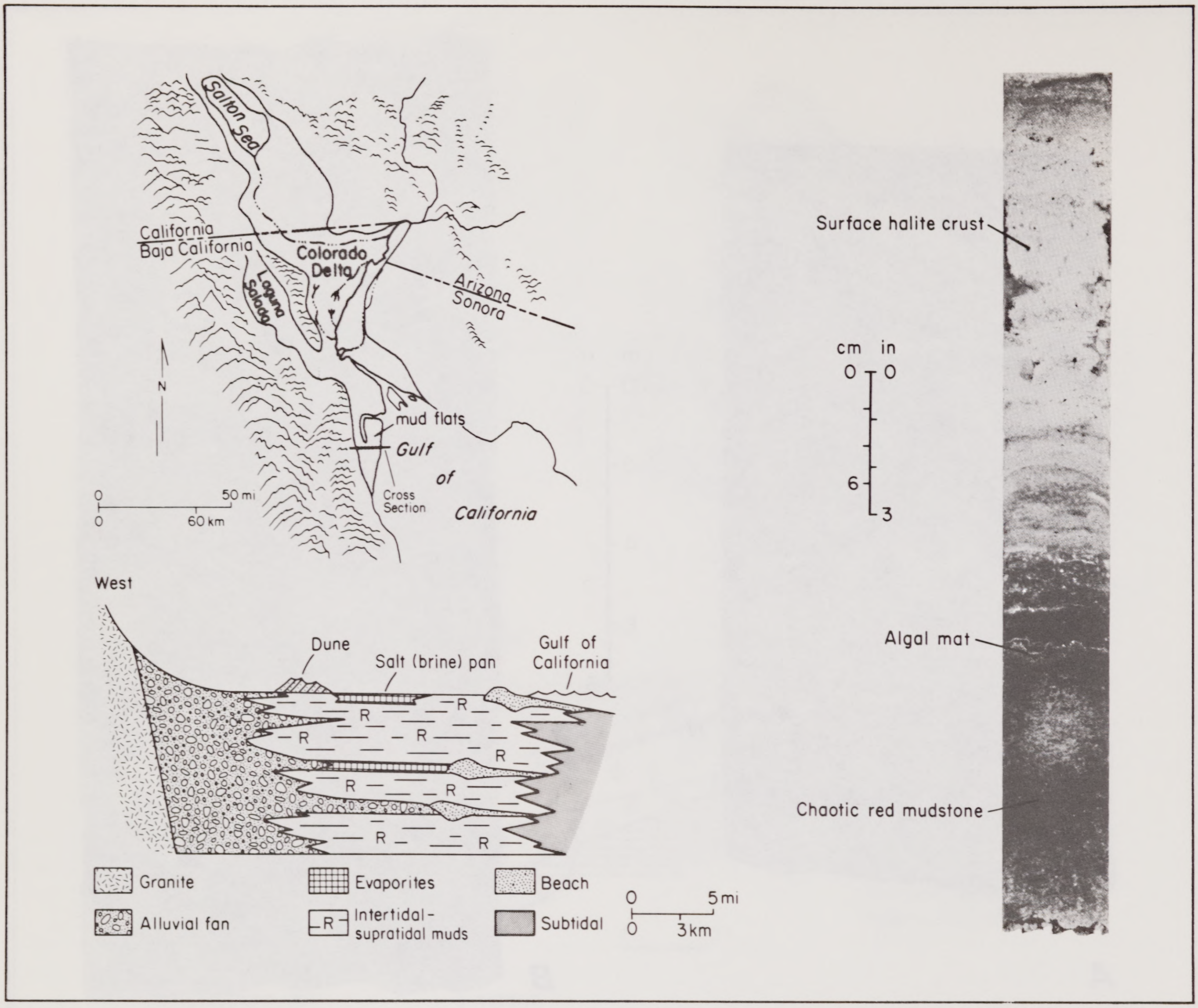


Figure 18. Regional map of northern Gulf of California showing coastal mud flats near mouth of the Colorado River and schematic cross section through mud flats. Core from brine pan (salt pan) at this locality shows salt deposited in brine pan overlying supratidal mud. From Handford (1980); modified from Thompson (1968) and Walker (1967).

upper Clear Fork cores, from laminated dolomite to nodular mosaic anhydrite, to laminated anhydrite, to "grass mat" anhydrite, may record sedimentation during a time of progressive increase in the extent and/or periodicity of brine pan flooding.

"Grass mat" facies are similar to the grasslike gypsum molds noted by Nurmi and Friedman (1977) in the Michigan Basin, where vertical crystals observed in laminated anhydrite are molds of primary gypsum crystals, either filled or replaced with halite. These crystal molds are irregularly six-sided when viewed parallel to bedding, and in a number of instances exhibit swallow-tail, gypsum-twinned upper terminations. Nurmi and Friedman (1977) suggested that the original grasslike gypsum crystals formed in shallow-water environments at the sediment-water interface, whereas lenticular gypsum crystals, parallel to bedding within the laminae, formed interstitially. The lack of grasslike molds in deeper water facies was attributed to anaerobic conditions in these areas and to probable degradation of sulfate minerals by sulfate-reducing bacteria.

Richter-Bernburg (1973) described "upright-standing gypsum crystals" in layered gypsum in Messinian evaporites (Miocene) of Sicily. These vertical crystals are unreplaced selenite twins with swallow-tail upper terminations. Thin layers of these swallow-tail crystals are a few centimeters thick and are comparable in size to upper Clear Fork "grass mat" pseudomorphs. Richter-Bernburg (1973) described crystals in these layers as being shaped like short grass leaves. However, in the Messinian rocks, layers with vertical selenite crystals are commonly from a decimeter to a few meters (4 inches to a few yards) thick. The largest selenite crystal observed by Richter-Bernburg (1973) was 6 m (20 ft) long. He suggested that these gypsum crystals formed on a subsiding, shallow-water platform, marginal to a deeper water, Messinian evaporite basin. Hardie and Eugster (1971), studying the same rocks, also favored a shallow-water, hypersaline environment.

Schreiber and Kinsman (1975) reported layered gypsum in the Montallegro Formation (Pleistocene) in southern Sicily. They noted a record of both mechanical deposition of gypsum into laminae and growth of vertically arrayed crystalline gypsum in shallow-water brines. These interpretations were applied to two types of gypsum layering observed in these rocks: (1) gypsum-detrital grain layers containing limonite-stained micritic carbonate and scattered foraminiferal tests and (2) crystalline gypsum layers containing crystals that are vertically elongate. Detrital layers were observed alternating with crystalline layers. Relating Montallegro rocks to modern occurrences of gypsum in solar salt ponds in California, Schreiber and Kinsman (1975) suggested that the crystalline gypsum of the Montallegro Formation formed by direct precipitation from saturated waters in shallow subaqueous environments, whereas the detrital laminae were deposited during floods in which the upper surface of the previously deposited crystalline layer was redissolved. Gypsum grains that make up the detritus were possibly precipitated at the air-water interface and then sank or may have been torn loose from growth sites at the sediment-water interface. Schreiber and Kinsman (1975) also noted elongate, vertical gypsum crystals that are continuous upward through multiple detrital laminae; an example of this is observed in upper Clear Fork rocks (fig. 17B). This occurrence, according to Schreiber and Kinsman (1975), suggests continued growth at crystal nucleation sites following periodic disruption of crystal precipitation by storm activity or periodic salinity changes. In upper Clear Fork rocks the preservation of such delicate detrital laminae across large original selenite crystals (fig. 17B) implies that crystalline halite replaced the gypsum rather than filled the crystal molds.

Massive Salt Deposits

Relatively massive salt deposits are clear or stained red brown, and are normally banded into layers 2.5 to 15 cm (1 to 6 inches) thick (fig. 19). Darker bands of halite are colored red brown from mudstone finely disseminated in a salt matrix. These darker layers alternate with relatively pure salt layers. The banding in the salt is distinctive of this facies and distinguishes this rock from other halite sediments. The same rock type has been observed in other salt-bearing units, such as the Salina Salt of Michigan (Dellwig, 1955; Nurmi and Friedman, 1977) and the Devonian Prairie Evaporites of Canada (Wardlaw and Schwerdtner, 1966), and is generally considered a subaqueous deposit.

Layers of relatively massive salt deposits in the upper Clear Fork and Glorieta Formations commonly have elongate, vertically arrayed halite crystals similar to those described by Arthurton (1973) in Lower Keuper salt beds at Cheshire, England. Arthurton demonstrated in laboratory evaporation pans that such textures can result from upward competitive growth of halite crystals from nucleation sites on the bottom of relatively shallow (2- to 10-cm-deep) brine pans.

The banding in upper Clear Fork-Glorieta massive salt is considered the result of multiple crystallization episodes in shallow, hypersaline waters. Boundaries between bands probably are in most instances the result of solution owing to abrupt changes in brine chemistry. Halite bands in these massive salt deposits are commonly separated by clay partings, which may be suspension-load detritus carried in periodic storm flooding of brine pans. It is our observation that in ponded saline waters containing considerable amounts of suspended clay, clay and salt commonly separate into discrete layers. This is an effect of timing of sedimentation. Settling of detritus begins almost immediately after flooding as waters become calm. However, formation of salt can require a period of evaporation, concentration, and mixing before halite saturation is attained. Thus, settling of detritus and salt precipitation can be distinctly different events.

Restriction and Salinities in Brine Pan Environments

Throughout the period of salt deposition in upper Clear Fork-Glorieta brine pans and salt-flat environments, restriction of the salt plain may have been maintained by continued progradation and aggradation of intertidal and supratidal carbonate facies on the seaward margin of the salt plain. Kinsman (1969) and Butler (1969) supported the concept of restriction by continued sabkha formation along the seaward margin of salt depositional environments. Kinsman noted that with formation of a broad, coastal, sabkha-like platform, continuous subsidence during the period of progradation would

> ...cause marine sediment facies to rise across the sediment belt. Continued infilling of the first-formed sabkha area with additional supratidal storm-wash, alluvial, eolian, and evaporite facies probably would occur. A fairly thick evaporite-bearing section could be formed, its thickness dependent on rate of subsidence and duration of sedimentation (Kinsman, 1969, p. 839).

As will be shown, during the final stages of development of brine pan facies successions, brine pans dried and were infilled by muds, and deposition in supratidal environments was predominantly in salt flats.

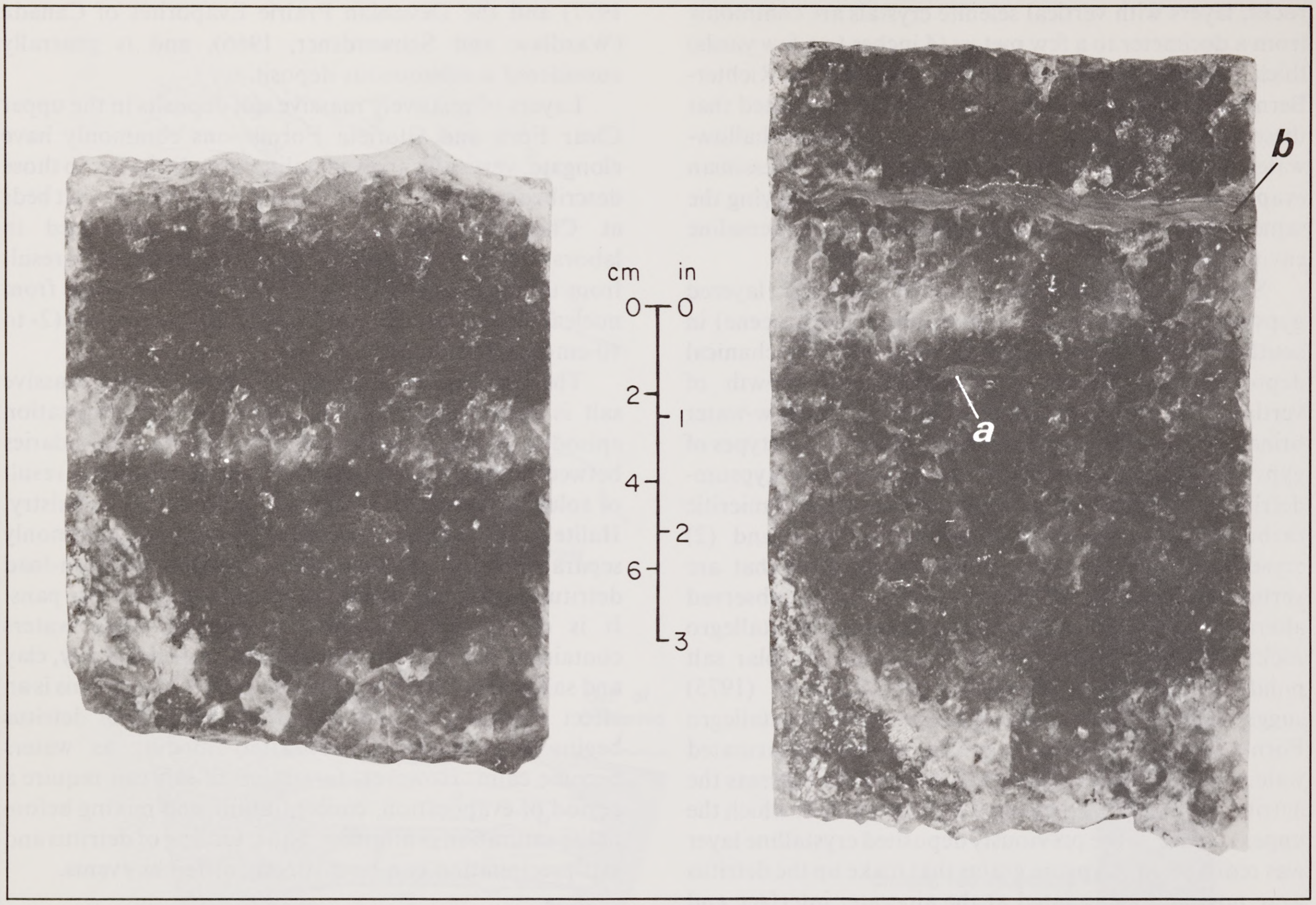


Figure 19. Massive salt facies from upper Clear Fork Formation. Alternating dark and light bands reflect varying amounts of disseminated red clay; minor intercrystalline clay at (a); clay band at (b) exhibits delicate internal laminations. Both samples from DOE-Gruy No. 1 Grabbe, depth 1,065.0 m (3,494 ft).

Steady-state salinity at gypsum or halite saturations in brine pan environments may have been maintained for long periods of time by dynamically balanced conditions of loss and addition of both brine waters and solute load. The hydrology of such a brine pan system is not a simple process of supply of marine waters through an inlet and subsequent reflux, as discussed by King (1947) and Scruton (1953). In broad shallow-water supratidal brine pans, supply of marine waters by tides and storms is certainly important, but other factors, such as terrestrial runoff and ground-water seepage from both marine and terrestrial environments, can affect brine concentrations. Ground-water seepage must be considered in terms both of supply of brine to surface waters during high water-table conditions and of downward percolation as pans dry out. Steady-state salinity concentration in ground waters is an important geochemical parameter since the ground-water environment can become a site of evaporite precipitation and near-surface diagenesis of previously deposited evaporites. Within brine pans, previously deposited salt provides a partial buffer to changes in salinity; that is, salt is redissolved and/or precipitated under varying conditions of solute saturation, thereby increasing or decreasing the total solute load of the brines.

There is a problem in referring to brine pans as supratidal systems. Supratidal brine pans at Bonaire in the Caribbean are in fact below sea level (Murray, 1969). However, Murray (1969) refers to sediments in these brine pans and on adjacent flats as supratidal deposits. Presumably, the term is used here in a geographic sense rather than in reference to an absolute tide level. In considerations of upper Clear Fork-Glorieta brine pan environments, the relation of the brine pan elevations to the level of adjacent seas cannot be determined from present research. Because of crustal subsidence beneath evaporite environments, brine pans may be intertidal or subtidal in terms of absolute relation to the level of Permian seas. However, upper Clear Fork brine pans are thought to have been landward of supratidal accretionary/progradational environments that acted to restrict evaporite pans from open-marine waters. Thus, in a paleogeographic sense, brine pans are landward of intertidal and supratidal facies, and the term "supratidal," as applied to upper Clear Fork-Glorieta brine pan facies, is used in this context.

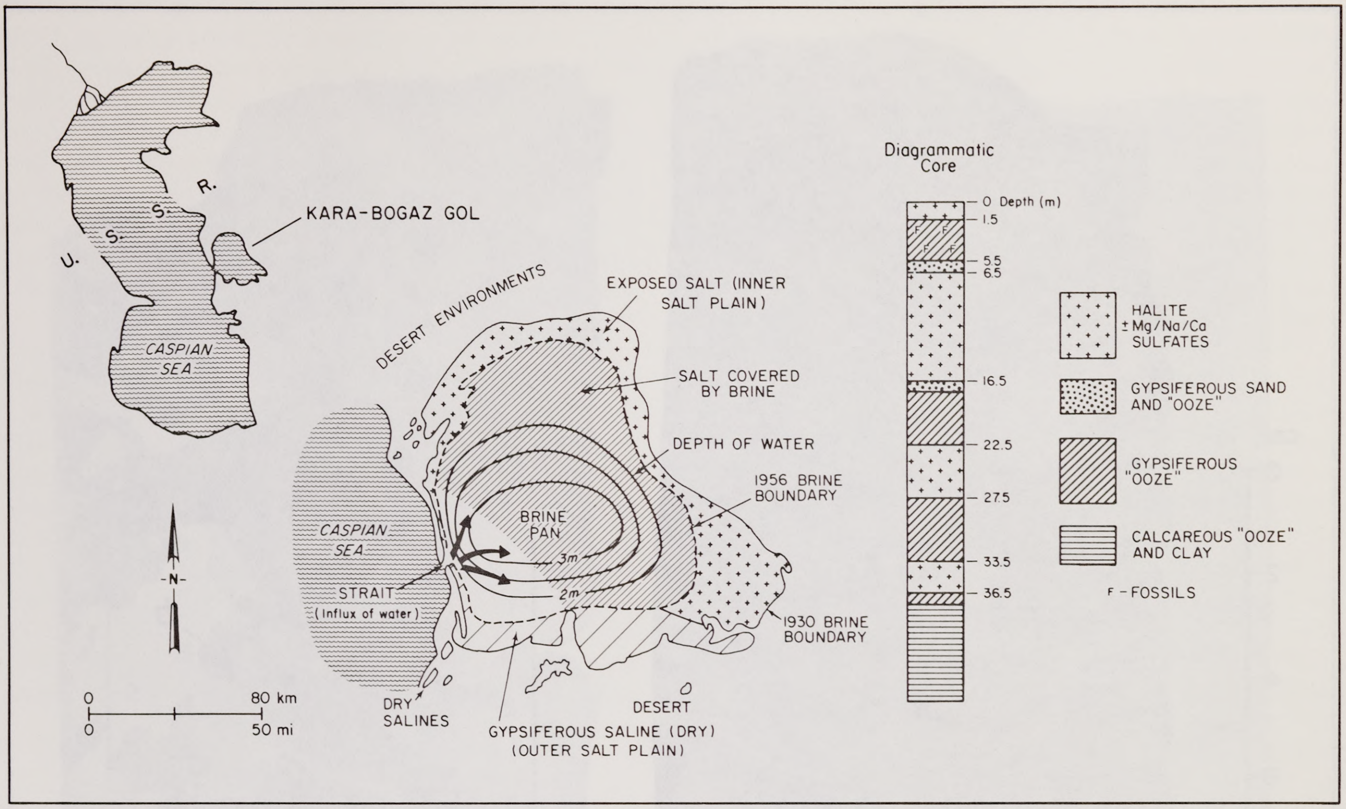


Figure 20. Modern brine pan and adjacent salt-flat environments at Karabogaz-Gol, Caspian Sea, USSR. Caspian Sea is a continental, saline-water body, whereas Karabogaz-Gol is a marginal shallow-water lagoon. Beneath the floor of the Karabogaz-Gol lagoon, up to 120 ft (37 m) of evaporites, including salt and gypsum, have been deposited. In addition, large quantities of magnesium, calcium, and sodium sulfates derived from Caspian Sea waters are associated with lagoon sediments. The lagoon passes landward into an encrusted salt flat and is separated from the Caspian Sea by an extended sand barrier broken only by a single, narrow strait. Bedrock is exposed in isolated places along the barrier. Water flows from the Caspian Sea through the strait into Karabogaz-Gol, which is at a lower elevation than the Caspian. There is no return flow, and no fresh-water streams flow into the lagoon from terrestrial areas to the east. Water is lost from the lagoon largely through evaporation. A balance exists between rate of inflow and rate of evaporation to create relatively stable levels of salinity near saturation of halite. A salinity gradient does exist across the lagoon, however, so that waters near point of inflow from the strait are relatively fresher. Drawing and descriptions adapted from Dzens-Litovskiy and Vasil'yev (1962).

A Modern Brine Pan Analog at Karabogaz-Gol

A modern example of a brine pan system at Karabogaz-Gol in the Soviet Union exhibits some of the sediment characteristics that may have been present during late Clear Fork and Glorieta time (Dzens-Litovskiy and Vasil'yev, 1962). Karabogaz-Gol is a shallow-water lagoon on the eastern coast of the Caspian Sea (fig. 20). The lagoon is 125 km (80 mi) wide; maximum water depth is 3 m (10 ft), which is a relatively small amount of bottom relief over such a large region. The lateral extent of the brine pan is similar to the lateral extent of brine pans that existed in the Texas Panhandle during late Clear Fork-Glorieta time. Salinity within the Karabogaz-Gol brine pan is maintained at a steady state over long periods of time by a balance between evaporation and supply of incoming solute-rich waters. We are not aware of studies of other hydrologic factors, although Dzens-Litovskiy and Vasil'yev (1962) note that there is little terrestrial runoff to the Karabogaz-Gol Basin. The brine pan extends landward into supratidal salt flats, as did upper Clear Fork-Glorieta brine pans. It is important to note, however, that the analog of Karabogaz-Gol is provided only as an example of some general characteristics, and that beyond scale, salinity balance, and general environmental distribution of brine pans and salt flats, there are many dissimilarities between Karabogaz-Gol and upper Clear Fork-Glorieta sedimentology. Karabogaz-Gol is a continental environment, and the types of salt deposited are different from those of marine deposits. Also, Karabogaz-Gol is separated from the Caspian Sea by a clastic barrier and possible structural elements, whereas it is inferred that the upper Clear Fork-Glorieta brine pan environments were restricted from open-marine waters by accretionary carbonate and clastic facies.

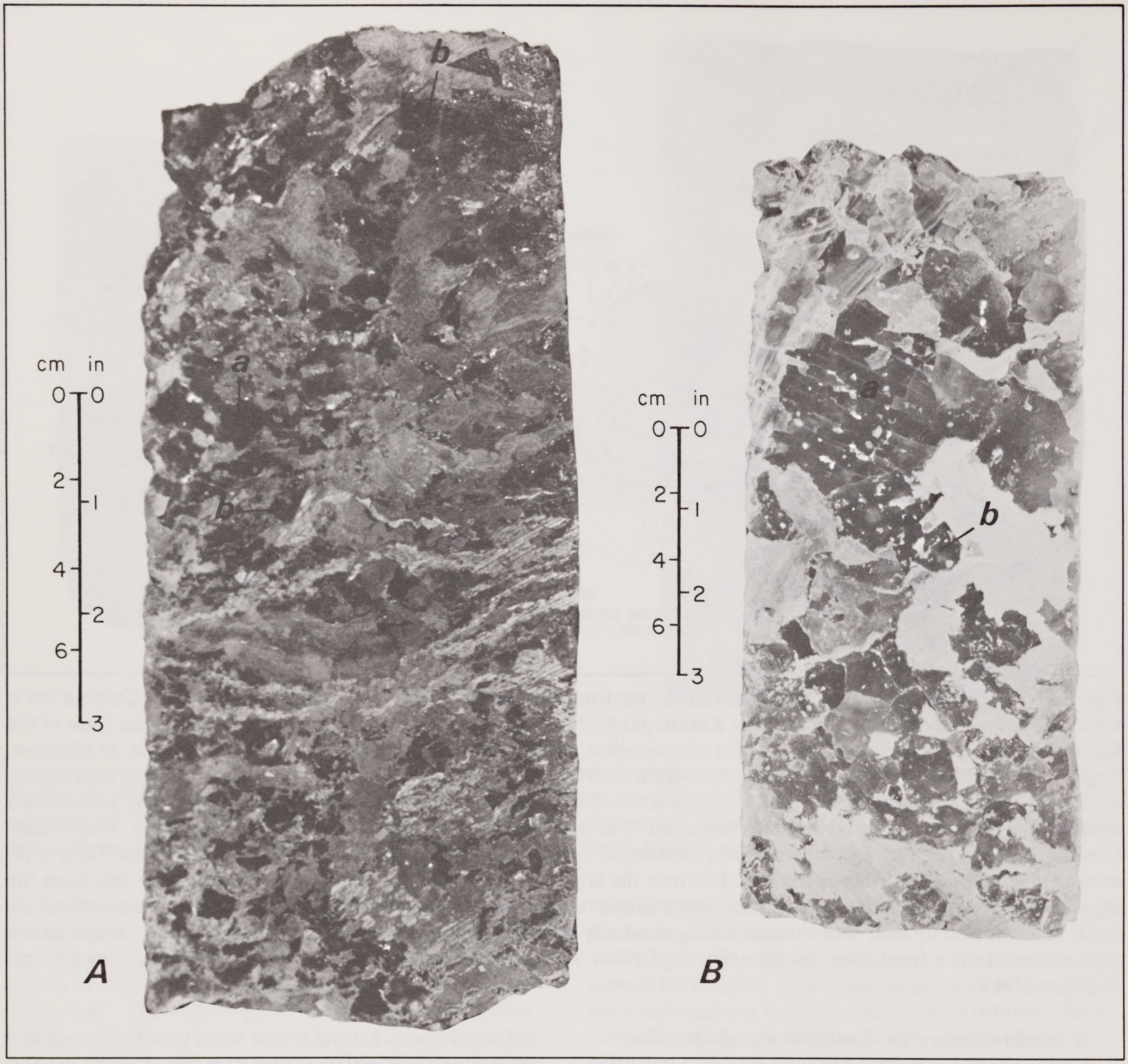


Figure 21. Chaotic mudstone-salt, upper Clear Fork Formation. Halite (a) is darker mineral; note euhedral boundaries of halite crystals contacting mud (b). (A) From DOE-Gruy No. 1 Grabbe, depth 971.7 m (3,188 ft). (B) From DOE-Gruy No. 1 Rex H. White, depth 709.6 m (2,328 ft).

SALT-FLAT DEPOSITIONAL SYSTEMS

Brine pan environments graded landward into salt flats, which were commonly exposed (figs. 2 and 3; tables 3 and 4). The transition from brine pan to salt-flat facies is marked by a large increase in the quantity of red clastic sediments, predominantly clay and silt, intercalated with evaporites. The distinction of brine pans versus salt flats suggests varied degrees of flooding on the upper Clear Fork-Glorieta salt plain, the salt flats being slightly emergent. Salt-flat sediments may include surficial salt crusts, which developed on the flats during periods of exposure and were not completely redissolved during recurrent floods. Much of the sediment record, however, may be of interstitial precipitation of evaporites within muds.

Salt-flat facies are predominantly chaotic mixtures of salt and red-brown mudstone, which range from mud containing scattered salt crystals to a crystalline salt containing intercrystalline mud (fig. 21). Chaotic

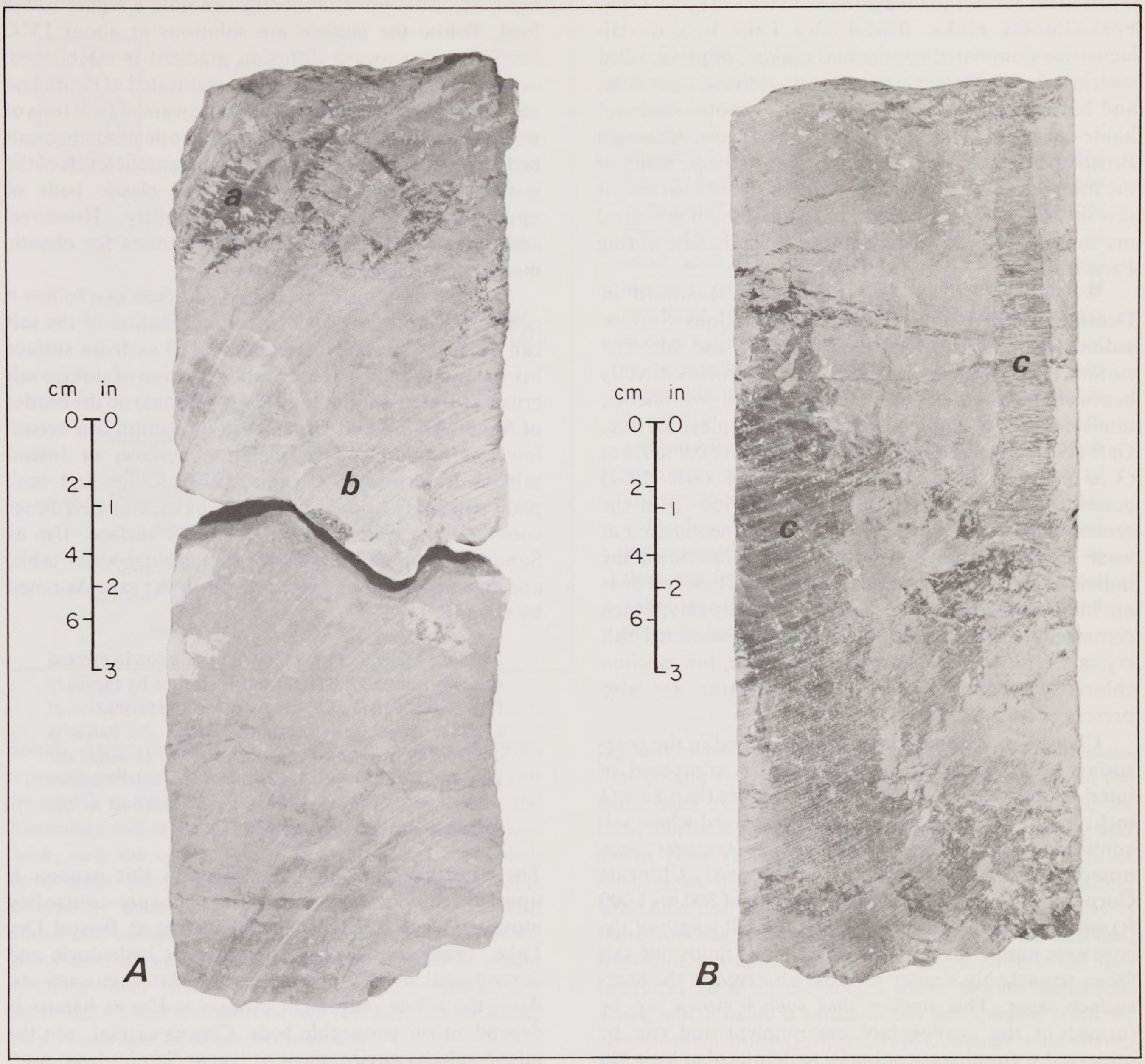


Figure 22. Mudstone facies in Glorieta Formation. (A) Halite filling chevron fractures at (a); nodular anhydrite at (b). (B) Large fracture-filling halite at (c). Both samples from DOE-Gruy No. 1 Rex H. White, depth (A) 713.5 m (2,341 ft), depth (B) 896.1 m (2,940 ft).

mudstone-salt textures have previously been termed "haselgebirge" (Arthurton, 1973). The banding that is so characteristic of massive salt beds deposited in brine pans is absent in these chaotic mudstone-salts, even where the mudstone-salt mixtures are predominantly halite. Bedding within chaotic mudstone-salts is obscure, and much of the sediment is highly deformed and disrupted. In mudstone-salt mixtures that are predominantly halite, crystal size is commonly 0.6 to 1.3 cm (0.25 to 0.5 inch). Isolated salt crystals, which grow displacively in mudstone beds, are typically much larger, up to as much as 4 cm (1.5 inches) in diameter. Halite shows crystal faces where it is in contact with mud. Halite crystals, which are surrounded by mud, typically grow in equal proportions in three dimensions, suggesting interstitial displacive growth. Cubes with zoned inclusions similar to displacively grown halite crystals observed by Arthurton (1973) are present in the upper Clear Fork and Glorieta deposits, although equidimensional crystals without zoned inclusions are more common in these rocks. Chevron-arrayed halite hopper crystals displace mud (fig. 22).

Chaotic mud-salt textures observed at Bristol Dry Lake in southern California by Handford (1981) are remarkably similar to mudstone-salt facies in upper Clear Fork-Glorieta rocks. Bristol Dry Lake is a fluvial-lacustrine-dominated continental sabkha, or playa, filled with interbedded terrigenous clastics, gypsum, anhydrite, and halite (Handford, 1981). Beds of chaotic mud and halite thicken into the central part of the playa. Although Bristol Dry Lake is a continental environment, many of the more local geochemical and depositional relations at this site may be analogous to conditions present in coastal marine evaporite environments in the Panhandle during Permian time.

We visited Bristol Dry Lake with Handford in December 1979 and made several observations: Surface sediments of Bristol Dry Lake are clay and silt. The surface itself is dry and blistered, but sediments directly beneath the surface are damp. A bed of chaotic mudstone-salt is exposed in trenches in the playa surface. Gale (1951) noted that this bed is at a depth of 0.9 to 2.1 m (3 to 7 ft) and is as thick as 2.1 m (7 ft). Gale (1951) described borings to as much as 46 m (150 ft) in the central part of the playa. These borings encountered at least seven beds of salt and salt-mud mixtures; the individual beds are as thick as 2.7 m (9 ft). These salt beds are interbedded with green, brown, and gray clay, which commonly contains salt-rich lenses and scattered salt crystals. The salt is predominantly halite, but calcium chloride, gypsum, glauberite, and celestite are also present (Foshag, 1926; Gale, 1951).

Chaotic mudstone-salt that we observed in the near-surface salt bed at Bristol Dry Lake is composed of interlocking halite crystals, commonly more than 3 cm (1 inch) in diameter; crystal facies are displayed where salt contacts intercrystalline mud. Similar textures were noted in core (provided by National Chloride Corporation) from a borehole to a depth of 300 m (1,000 ft) within Bristol Dry Lake. Along the full length of the core were numerous salt beds with chaotic mudstone-salt facies remarkably similar to those observed in the near-surface layer. This implies that such textures can be formed in the near-surface environment and can be preserved with subsequent burial to depths of at least 300 m (1,000 ft); that is, salt at depth in Bristol Dry Lake can reflect depositional textures from near-surface environments. Applying this to chaotic mudstone-salt textures in the Texas Panhandle allows the possibility that such deeply buried facies also formed in the near-surface environment.

Concerning the origin of chaotic mudstone-salt in Bristol Dry Lake, Foshag (1926) suggested that crystallization of the salt in muds occurred beneath the uppermost mud layers on dry playa surfaces. Foshag (1926) considered differences of temperature between surface layers and mud sediments at depth critical for establishing a diffusion of solute downward, particularly within the capillary fringe of the ground-water table, to form supersaturated solutions at depth. Brine near the surface is heated to a temperature of 40°C (104°F) or more by insolation and thereby can hold a higher solute load. Below the surface are solutions at about 15°C (68°F). A downward diffusion gradient is established, causing solutions to become supersaturated at depth and halite to be precipitated. We are not aware of field tests of this phenomenon. It may be that chaotic mudstone-salt beds were deposited interstitially at persistent levels of the ground-water table, coincident with clastic beds of appropriate porosity and permeability. However, additional study of depositional processes for chaotic mudstone-salt facies is required.

Surface salt crusts in exposed salt flats can follow a complex history of deposition. Precipitation of the salt can be from beneath the crust as well as from surface brines. Glennie (1970) described formation of surface salt crusts at Um as Samim (mother of poisons) on the border of Saudi Arabia and Oman. Um as Samim is a broad, low-relief, salt-encrusted deflation surface, or inland sabkha, as termed by Glennie (1970). Eolian and wadi plain sediments bound the inland sabkha, and sand dunes commonly migrate across the sabkha surface. Um as Samim is at or below a fluctuating ground-water table, and free water can be present beneath the salt. As noted by Glennie:

> In desert areas, sodium chloride in solution in ground water is normally brought to the surface by capillary flow that is balanced by evaporation and formation of a halite crust. This means that when the halite is covered by a permeable sediment such as sand, the upward flow of less saline water from below causes solution of the salt and its recrystallization at the surface (Glennie, 1970, p. 63).

The direction of solute movement in this process is upward and opposite the temperature-controlled movement suggested by Foshag (1926) at Bristol Dry Lake, again emphasizing the complex hydrologic and depositional history possible in salt-flat environments. Also, the solute movement process at Um as Samim is dependent on permeable beds. Clay is carried into the inland sabkha environment at Um as Samim from wadi streams, and salt, which precipitates in the clay, can be preserved as lenses.

On the surface of the salt crust at Um as Samim, the salt can be intermittently dissolved by rainwater, causing wind-deposited sand that has accumulated in the salt crust to migrate downward through the salt. Thus, vertical movements and redistribution of halite and nonhalite impurities within salt crusts may be a typical phenomenon of surface exposure to intermittent wetting. Wind deflation and transport of salt and sand at Um as Samim are common, resulting in lateral movements of surface sediments.

A common feature of salt flats is buckling of surface crusts into large polygons. This was observed by Vonder Haar (1972) at Laguna Mormona on the west coast of Baja California, and by Madigan (1930) on salt lakes of

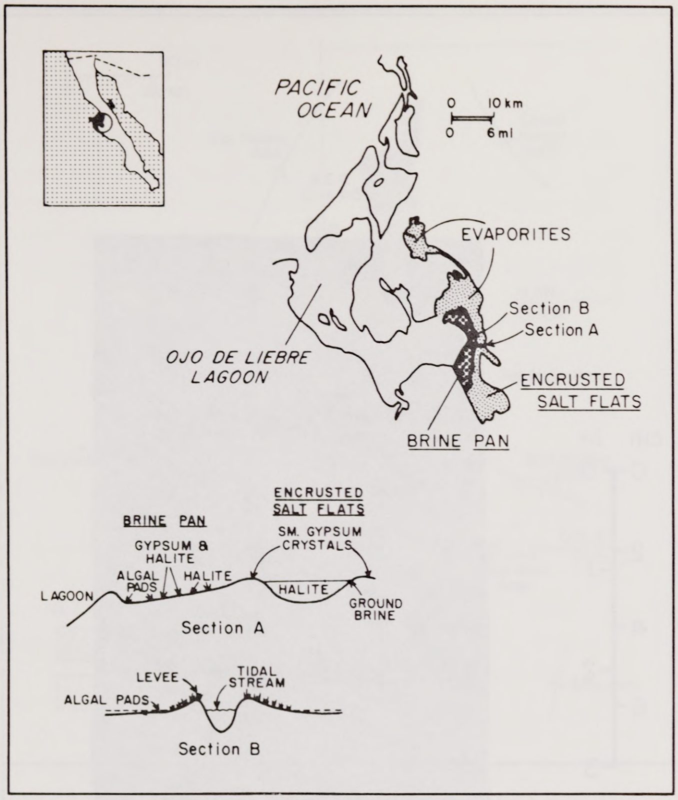


Figure 23. Coastal sabkha environments of Laguna Ojo de Liebre, described by Phleger (1969) on the west coast of Baja California, Mexico. Evaporite areas are cut off from main lagoon by barrier of sand, shell, and mud (Section A), and from tidal streams, extending through barrier, by levees of sand and mud (Section B). Flooding across barriers occurs with higher spring and storm tides. Flooding is controlled by gentle upward gradient into supratidal areas. Near the lagoon, an algal mat is forming over aragonite muds. Gypsum accumulates in higher intertidal zone. Halite with gypsum increases updip. During periods of continuous, high-velocity onshore winds, coincident with spring tides, extreme flooding of high supratidal areas occurs. Wind-tidal surges, as they are forced updip, redissolve halite, which is subsequently precipitated from the concentrated brine in high supratidal environments.

South Australia. At Um as Samim, Glennie (1970) reported salt polygons bounded by walls of buckled salt up to 1.2 m (4 ft) high. Madigan (1930) noted in the Australian salt lakes that where the crust is a foot or more thick, only the upper inch or so of the crust is buckled. With such processes as continued infilling of voids created by such large displacive movements, or with burial and compaction of adjacent muds, the preserved facies record following salt polygon formation would certainly bear the disruptive character commonly observed in chaotic mudstone-salt sediments in the upper Clear Fork and Glorieta Formations.

At Ojo de Liebre on the west coast of Baja California, coastal evaporite environments grade from brine pans landward into salt flats (fig. 23). This modern area has been described by Wittich (1916a, b), Phleger and Ewing (1962), Holser (1966), Kinsman (1969), and Phleger (1969). The transition from brine pans to salt flats at Ojo de Liebre is controlled by a gentle upward gradient into the salt flats. Similar topographic changes may have controlled the distribution of upper Clear Fork-Glorieta brine pans and salt flats. Brine pan deposits at Ojo de Liebre are algal-mat-bound aragonitic sediments, which pass updip into gypsum and halite facies. Gypsum accumulates in the higher intertidal zone, and the amount of halite present with the gypsum increases updip (Phleger, 1969).

The brine pan and salt-flat systems at Ojo de Liebre are landward of coastal lagoons and are cut off from these lagoons by barriers of sand, shell, and mud. Tidal streams that extend through the barrier are separated from the brine pans by levees of sand and mud. Flooding across these barriers and levees occurs with higher spring and storm tides (Phleger, 1969). Only during periods of continuous, high-velocity onshore winds (the prevailing wind direction), which are coincident with spring tides, is there flooding of supratidal areas. During these episodes, low-velocity wind-tidal surges redissolve halite in the high intertidal zone as the surges move toward supratidal areas, where halite is subsequently precipitated from the concentrated brine (Phleger, 1969). Similar wind-driven tidal surges are a logical mechanism for flooding vast supratidal flats, such as those present in the Texas Panhandle during Permian time.

Wittich (1916b) reported the succession of facies underlying the supratidal flats at Ojo de Liebre as (1) very fine quartz sand, overlain by (2) brine-saturated, putrid organic muds with algal remains, capped by (3) a salt layer as thick as 30 cm (12 inches). Wittich's (1916a, b) descriptions are important since they predate modern salt-mining activity in this area. Holser (1966) noted up to 1.3 m (4.3 ft) of halite in the surface salt layer, mixed with gypsum, polyhalite, and windblown sand. Holser also noted near-surface diagenetic replacement of gypsum by polyhalite in ground waters of very high salinities, suggesting that mineral equilibrium in salt crusts is constantly evolving as interstitial brine chemistry evolves.

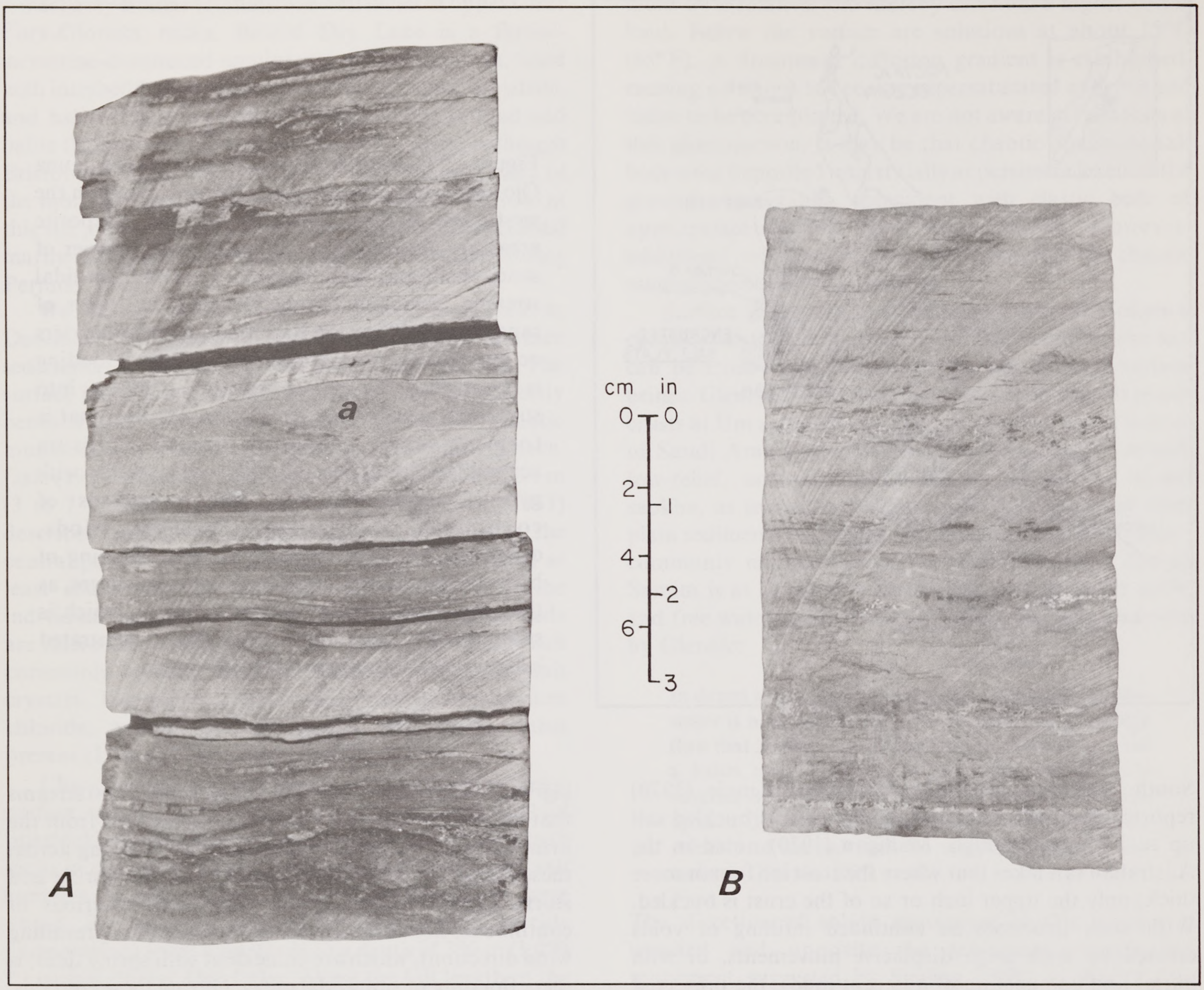


Figure 24. Laminated mudstone-siltstone facies of the Glorieta Formation. (A) Ripple-drift cross-laminations at (a). From DOE-Gruy No. 1 Grabbe, depth 955.9 m (3,136 ft). (B) From DOE-Gruy No. 1 Rex H. White, depth 733.7 m (2,407 ft).

MUD-FLAT DEPOSITIONAL SYSTEMS

General Relations

In the central Texas Panhandle during Glorieta time, evaporite sedimentation was periodically interrupted by the deposition of mud and silt in mud-flat depositional systems (figs. 2 and 4; table 3). Mud and silt may have been supplied to the mud flats by (1) eolian processes, (2) tidal surges carrying suspension-load detritus, and/or (3) periodic runoff from updip alluvial systems. Wind may have been important both in transporting brine into evaporite environments (wind-driven tides) and in redistributing sediments during periods of surface desiccation. In part, the mud-flat surface may have been a deflation-aggradation surface in equilibrium, deflation being controlled by the elevation of ground water.

Mud-flat facies in the Palo Duro Basin are composed predominantly of mudstone and interlaminated mudstone-siltstone (figs. 22 and 24). Laminated mudstone-siltstone is light to dark red-brown. Laminations are up to 1.5 cm (0.6 inch) thick (fig. 25). Thicker laminations are predominantly siltstone and commonly exhibit ripple-drift cross-laminations. Wavy ripple form of thicker laminations is common, as is flasering of these wavy laminae. Starved ripple-form lenses of siltstone encased in mud-rich laminae suggest traction deposition of migrating ripples. Nodular anhydrite is common.

Beds of red-brown mudstone are interbedded with laminated mudstone-siltstone (fig. 22). Nodular anhydrite is common in mudstone beds, as are displacive

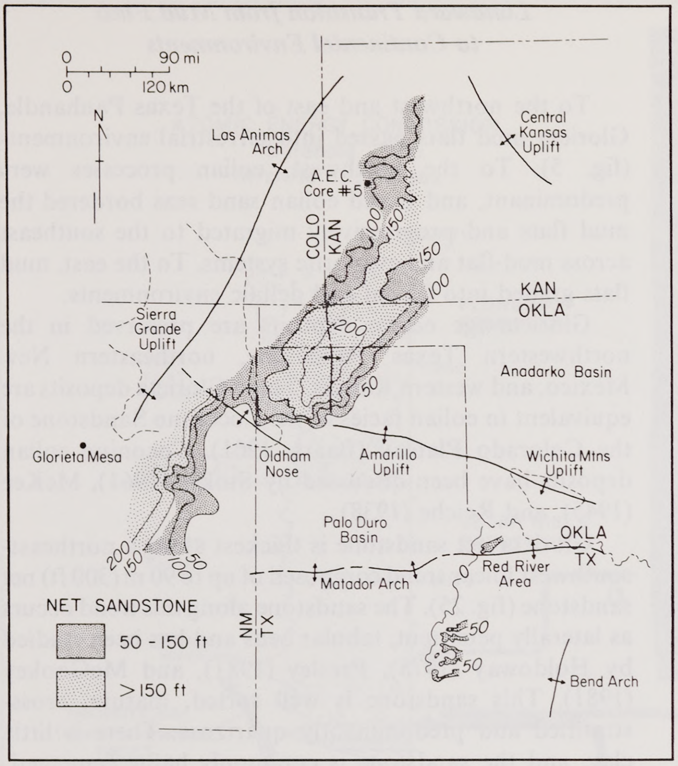


Figure 25. Net sandstone in Glorieta Sandstone and equivalent rocks in north Texas. Thickest net sandstone in Glorieta occurs in northeast-oriented trend of eolian sheet sandstones from eastern New Mexico to western Kansas. The Glorieta Sandstone in this area is predominantly in the subsurface. Net-sandstone values in western Kansas from Holdoway (1978). The San Angelo Sandstone in north Texas was deposited in fluvial-deltaic environments. Net-sandstone values are from G. E. Smith (1974).

halite hopper crystals. Mudstone is commonly soft and structureless when wet.

These mudstone and siltstone facies may be considered analogous to deposits observed in modern evaporitic mud flats. For example, modern tidal mud flats southwest of the Colorado River delta in the northern Gulf of California contain intercalated evaporites (Butler, 1970; Kinsman, 1969; Thompson, 1968, 1975; Walker and Thompson, 1968; Walker, 1967; fig. 18). The mud flats have prograded seaward by deposition of suspended mud from tidal surges. The mud is derived from the Colorado River, which discharges into the Gulf of California. Suspended-load detritus is circulated to the northwestern corner of the Gulf, where maximum mud-flat accretion has occurred. The tidal-flat facies interfinger updip with alluvial fan sediments derived from coastal mountains. Tidal-flat sediments are mainly clay and silt and are typically laminated. Laminations in intertidal facies are commonly disrupted by bioturbation (Thompson, 1968, 1975). Intertidal sediments aggrade to the level of the supratidal flats, where only minor amounts of the finest silt and clay are supplied by spring- and storm-tidal floods. A supratidal brine pan has formed in a large low-relief depression on the mud-flat surface. This brine pan is further isolated by mud or beach ridges. The brine pan is flooded by spring tides and commonly contains shallow water. The sediment surface within the brine pan is covered by algal mat. Evaporites crystallize below and above the algal mat as salinities in the brine pan increase during evaporation and brine mixing. Evaporites exhibit interlayers of algal-mat-derived organics, gypsum crystals, halite, tide- and wind-transported silt and clay, and micaceous sand washed from upland alluvial areas. Mud flats adjacent to brine pans are salt encrusted. On the high flats, away from brine pan environments, the brown and reddish-brown muds are highly disturbed by extensive desiccation and interstitial precipitation of gypsum. Parts of the high flats are inactive, possibly owing to evaporite crystallization, which elevates the surface (Thompson, 1968, 1975).

The Ranns of Kutch, India, described by Glennie (1970) and Glennie and Evans (1976), offer an example of supratidal flooding over great distances. The scale of this flooding in terms of distance inland is analogous to the scale of flooding across Glorieta mud flats. The Ranns of Kutch are evaporitic supratidal flats that extend up to 300 km (185 mi) inland along narrow coastal embayments. Water is driven landward from the Arabian Sea, up tidal estuaries, and onto these mud flats by prevailing offshore winds during the annual monsoon season. Mud-flat sediments are laminated silty clay and clayey silt, grading into sandier sediments toward the margins of the Ranns, near alluvial outwash fans and along the seaward margin of the flats. A surface halite crust, as thick as 5 to 8 cm (2 to 3 inches), remains after ebb of flood waters and evaporation of surface water. Gypsum crystals grow from brine ground water within the mud-flat sediments. Much of the halite crust is dissolved each year with renewed flooding, although historical evidence suggests that net accumulation of halite has been as much as 90 to 120 cm (35 to 47 inches).

Carbonate content of the mud-flat sediments is extremely low. Eolian transport of sand and silt, as well as halite and gypsum, occurs during periods of surface desiccation. Fine-grained clastic sediment supply to the Ranns is largely suspension load from nearby rivers. Mud is transported along shore from the nearby Indus River delta and is subsequently carried onto the mud flats by monsoon storm tides. Both fine and coarse siliciclastic sediments are also fed from terrestrial areas onto the landward parts of the Ranns by intermittent streams (Glennie, 1970; Glennie and Evans, 1976).

Seaward Transition from Mud Flats to Sand Flats

To the south of the Palo Duro Basin, Glorieta mud-flat facies grade into littoral and shelf facies composed of sandstone intercalated with dolomite (fig. 2). These facies were not observed in core in this study. In drill cuttings these sandstones are white, gray, or red, and very fine to medium grained. Sand grains are commonly subrounded to rounded and are typically free, an indication that the in-place rocks are somewhat friable. Dolomite intercalated with the sandstone is generally buff to brown, finely crystalline or sucrosic and commonly contains anhydrite, chert, oolites, and limestone.

These Glorieta sand-rich systems crop out in central New Mexico and were described by Milner (1978) as deposits of prograding barrier-island systems that developed during low stands of sea level. Milner (1978) observed beach, upper-shoreface, middle-shoreface, lagoon, and tidal-channel facies in these outcrops.

In modern mud-rich tidal flats, barrier systems commonly form in higher energy environments along the seaward margin of the flats, even where the clastic system is sand poor. Well-developed barrier systems are present at Laguna Madre along the South Texas coast, where broad wind-tidal flats are inland from the barrier (Fisk, 1959; Miller, 1975), and along the coastal mud flats on the northwest coast of the Gulf of California (Thompson, 1968, 1975). Thus, it is reasonable to suggest that similar systems formed the seaward margin of Glorieta mud flats.

Silver and Todd (1969) suggested that Glorieta sandstones interbedded with dolomite in the northern Midland Basin are continental (predominantly eolian) and nearshore facies. However, presentation of detailed facies analysis was beyond the intent of their study, and their conclusions in this regard were largely conjectural.

Studies of Guadalupian-age, back-reef sandstones interbedded with carbonates in southeastern New Mexico have suggested that these sandstones were deposited in shallow marine-shelf environments (Ball and others, 1971; Neese and Schwartz, 1977; D. B. Smith, 1974). However, the lack of available energy to transport sand in expansive shelf waters must be addressed if such an environmental interpretation is to be applied to Glorieta rocks.

Landward Transition from Mud Flats to Continental Environments

To the northwest and east of the Texas Panhandle, Glorieta mud flats passed into terrestrial environments (fig. 5). To the northwest, eolian processes were predominant, and broad eolian sand seas bordered the mud flats and progressively migrated to the southeast across mud-flat and evaporite systems. To the east, mud flats graded into fluvial and deltaic environments.

Glorieta-age eolian deposits are preserved in the northwestern Texas Panhandle, northeastern New Mexico, and western Kansas. These Glorieta deposits are equivalent to eolian facies of the Coconino Sandstone of the Colorado Plateau (Baars, 1961). Coconino eolian deposits have been discussed by Stokes (1961), McKee (1945), and Reiche (1938).

Glorieta net sandstone is thickest along a northeast-southwest linear trend composed of up to 90 m (300 ft) net sandstone (fig. 25). The sandstone along this trend occurs as laterally persistent, tabular beds and has been studied by Holdoway (1978), Presley (1981), and McGookey (1981). This sandstone is well sorted, mature, cross-stratified and predominantly quartzose. There is little clay, and the sandstone is commonly halite cemented. Cross-stratification is in large-scale sets and in ripple-form laminae. Geometry of large eolian cross-stratification sets is difficult to determine in core. What is seen in core are extremely smooth, planar laminae, which typically dip at angles of 20° to 30°, and up to a maximum of 34° (fig. 26). These planar laminae commonly exhibit bimodal grain size, which occurs as alternations of laminae composed of fine- to medium-grained sand and laminae composed of coarse-grained silt to very fine grained sand. This is a distinctive eolian texture described by numerous writers (Glennie, 1970; Bagnold, 1941; McKee, 1945; Hunter, 1977). Bimodal laminae may have been formed by a combination of migrating wind-ripple trains and grainfall (gravity settling of saltation projectiles and wind-suspension load), according to processes described by Hunter (1977). Possible grainflow (avalanche) laminae also described by Hunter were observed (fig. 26).

Within the transition zone from mud flats to eolian flats in the northwestern Texas Panhandle are multiple, upward-coarsening, regressive cycles of mud-flat and eolian facies. These appear on gamma-ray logs as upward-decreasing radioactivity at the base of eolian sandstone beds (figs. 26 and 27). As a group these cycles exhibit an overall basinward migration of terrestrial facies.

To the east of the Palo Duro Basin, Glorieta-age fluvial and deltaic deposits crop out as the San Angelo Sandstone of north Texas and the Duncan Sandstone of southwestern Oklahoma (G. E. Smith, 1974; Presley and others, 1980; fig. 25). Fluvial-deltaic sediments prograded to the southeast across mud flats and shelf deposits late in

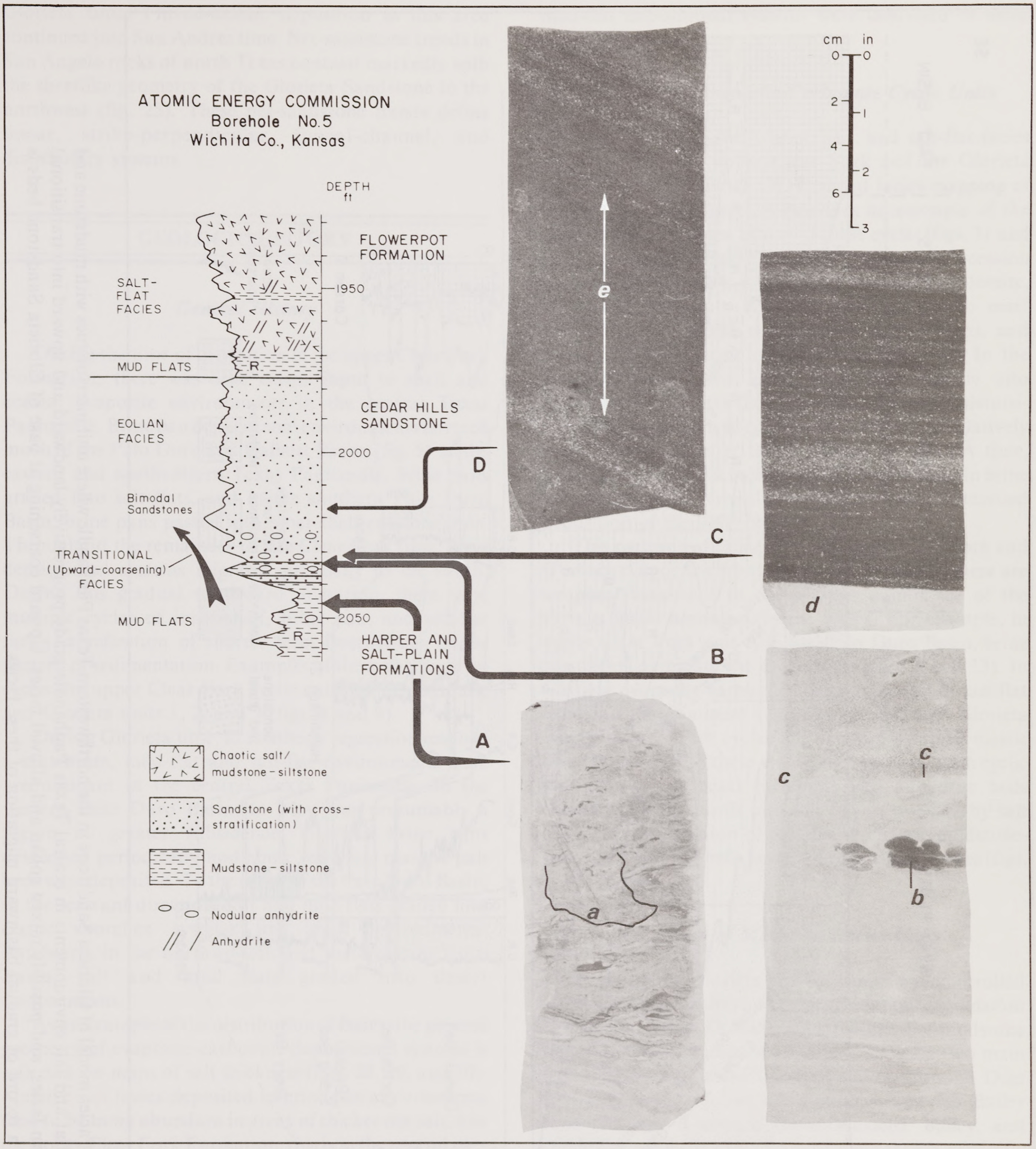


Figure 26. Core descriptions and mud-flat and eolian sandstone facies of Cedar Hills (Glorieta) Sandstone, in AEC Core No. 5, Wichita County, western Kansas. Core location in figure 25 and core discussed by Holdoway (1978). (A) Mud-flat facies exhibit interlaminae of siltstone and mudstone; bedding is disturbed; possible slump disruption outlined at (a); depth 623.3 m (2,045 ft). (B) Laminated siltstone capped by sandstone exhibits mud-flat to wind-flat transition facies; nodular anhydrite at (b); flowage structures at contact (c) suggest soft-sediment loading of mud and silt by sand; depth of sample 619.3 m (2,032 ft). (C) Bimodal eolian sandstones exhibit interlaminae of differing grain sizes and are halite cemented; fracture-filling halite (d) is at bottom of sample, depth 619.4 m (2,032 ft). (D) Bimodal eolian sandstone with high-angle cross-stratification exhibits possible grainflow bed (e) with inverse grading and may be considered deposit from avalanche down dune face, depth 614.8 m (2,017 ft). Samples provided by L. F. Dellwig, University of Kansas.

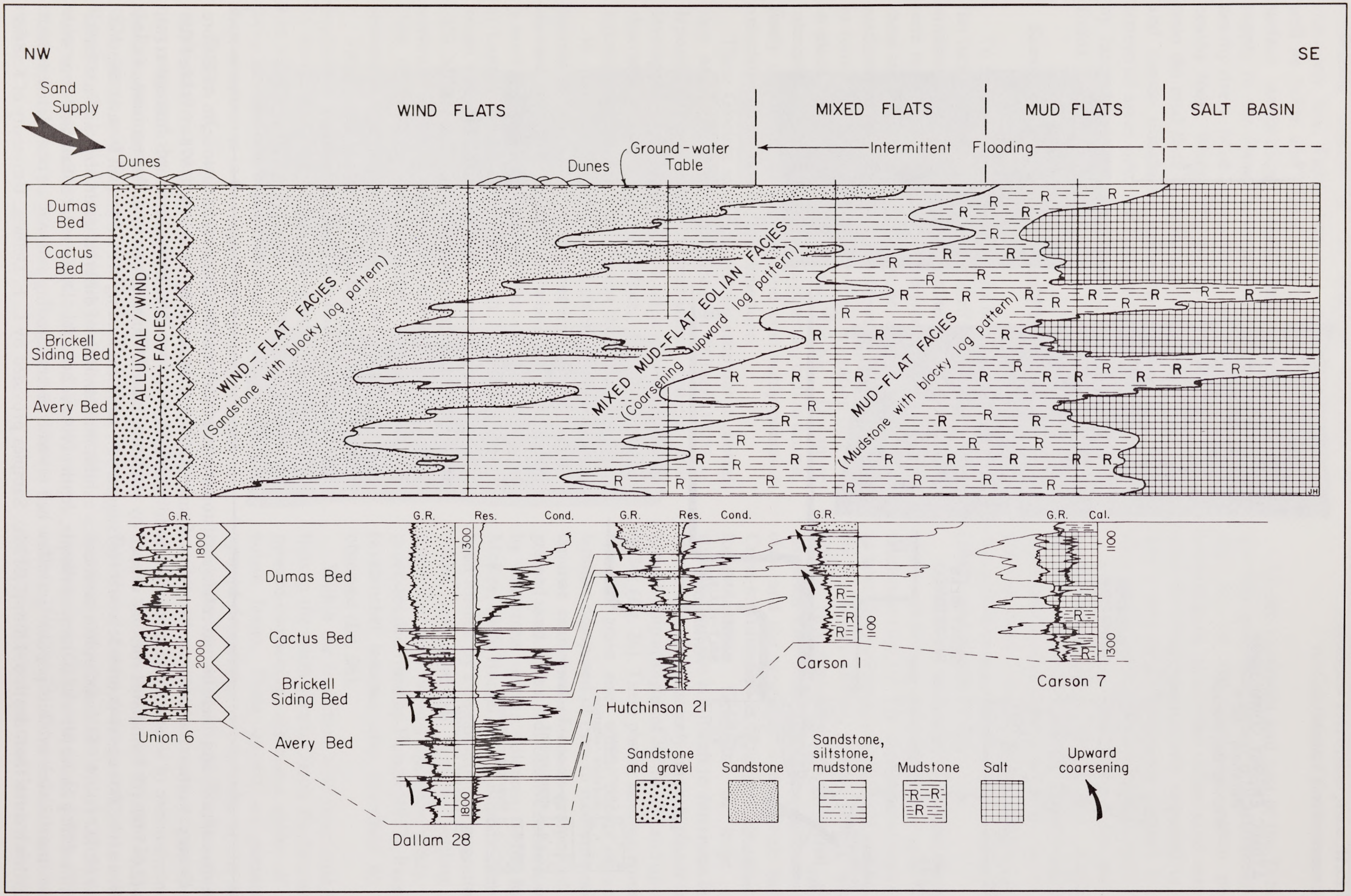


Figure 27. Facies model of Glorieta Sandstone in the northwestern Texas Panhandle where unit intertongues with mudstone and salt. Mud-flat and salt environments in central Texas Panhandle grade progressively landward and upward into transitional facies, eolian facies, and possibly mixed eolian and alluvial facies. Upward coarsening at base of Glorieta Sandstone beds is considered a record of gradual basinward migration of these facies.

Glorieta time. Fluvial-deltaic deposition in this area continued into San Andres time. Net-sandstone trends in San Angelo rocks of north Texas contrast markedly with the sheetlike geometry of the Glorieta Sandstone to the northwest (fig. 25). These net-sandstone trends define linear, strike-perpendicular, fluvial-channel, and distributary systems.

GEOLOGIC HISTORY

General History

During the time of deposition of the upper Clear Fork Formation, there was little clastic input to shelf and coastal evaporite environments in the central Texas Panhandle. Brine pan depositional environments covered much of the Palo Duro and Dalhart Basins (fig. 5). In the eastern and northeastern Texas Panhandle, brine pans graded into salt flats, and in the southern Palo Duro Basin, brine pans passed into inner-shelf environments. Throughout the remainder of late Clear Fork time, these depositional systems migrated gradually to the south. During this gradual southward migration, there were multiple cycles of inner-shelf, brine pan, and salt-flat facies, a reflection of shorter term fluctuations in the pattern of sedimentation. Examples of these shorter term cycles are upper Clear Fork cyclic units 1A through 2D, and Glorieta units 1, 2, and 3 (figs. 8 and 9).

During Glorieta time, as southerly regression reached a maximum, mud-flat and salt-flat environments were predominant in the central Texas Panhandle. In the western Palo Duro Basin, in what was presumably a region of greater subsidence, Glorieta brine pans developed periodically and some relatively massive salt beds were deposited. To the south of the Palo Duro Basin, in the seaward direction, salt and mud flats graded into clastic shoreline systems and shelf environments. Landward, in the northwestern and eastern Palo Duro Basin, salt and mud flats graded into desert environments.

As an example of the distribution of facies, the general geometry of evaporite-carbonate depositional systems is reflected on maps of salt thickness (figs. 28, 29, and 30). Massive salt facies deposited in brine pan environments tend to be more abundant in areas of thicker net salt. For the upper Clear Fork Formation, this is in the central part of the Palo Duro Basin (fig. 28); for the Glorieta Formation this is in the west-central Palo Duro Basin (fig. 29). Values of net salt for the upper Clear Fork Formation exclude much of the mudstone typically intercalated with salt in salt-flat and mud-flat facies in this unit. However, a map of net-salt-bearing rocks in the Palo Duro Basin does reflect thick mudstone with the salt (fig. 30). Thickest accumulations of upper Clear Fork salt-bearing rocks are to the north of thickest net salt and show that salt- and mud-flat depositional systems were landward of brine pan environments.

Evolution of Evaporite-Carbonate Cyclic Units

Cycles of inner-shelf, brine pan, and salt-flat facies occur in both the upper Clear Fork and the Glorieta Formations (figs. 8 and 13). Detailed facies mapping of upper Clear Fork unit 2A provides an example of the stages of development of one of these cycles (figs. 31 and 32). In the central Palo Duro Basin, a typical succession of facies in unit 2A is (1) algal-laminated dolomite, grading upward into (2) laminated and "grass mat" anhydrite interbedded with massive salt deposits, and capped by (3) chaotic mudstone-salt (fig. 31). In the southern Palo Duro Basin, these facies grade into dolomite; to the north they grade into chaotic mudstone-salt. This succession is considered a record of relatively rapid transgression at the beginning of unit 2A time, followed by a gradual basinward (regressive) shift in brine pan and salt-flat environments during the continued deposition of the unit (fig. 32).

This pattern is duplicated in all upper Clear Fork and Glorieta evaporite-carbonate cycles. However, there are temporal variations in the relative dominance of the various facies among different cycles. For example, in upper Clear Fork unit 1, in the Palo Duro Basin, brine pan facies dominate the cyclic units (figs. 2 and 13). In Glorieta evaporite-carbonate units 1, 2, and 3, salt-flat facies are predominant (figs. 2 and 14); also Glorieta evaporite-carbonate cycles are overlain by thick clastic beds. But even with these temporal variations, each cyclic unit consists of basal carbonate and anhydrite beds extending to the north into salt facies, overlain by salt beds with a succession of massive to chaotic mudstone-salt. The evaporite beds grade south into carbonates (figs. 8, 33, 34, and 35).

Evolution of Mud-Flat Facies Units

Geometry of Glorieta red-bed units was controlled both by basin structures and by progradation/aggradation of mud-flat facies. Considering structure, net-mudstone maps for Glorieta units A, B, and C indicate two main depocenters: the Castro trend extending through Deaf Smith, Castro, and Swisher Counties, and the Bailey trend through Roosevelt (New Mexico), Bailey, and Lamb Counties (fig. 36). Both of these trends generally coincide with structurally low areas as defined by basement structure maps (Nicholson, 1960). It is suggested that subsidence in these areas continued through Glorieta time, although the major period of tectonic activity creating the Palo Duro Basin and adjacent uplifts was during the Pennsylvanian and Early Permian (Nicholson, 1960).

In addition to these structural relationships, Glorieta clastic depocenters shifted from the Castro trend

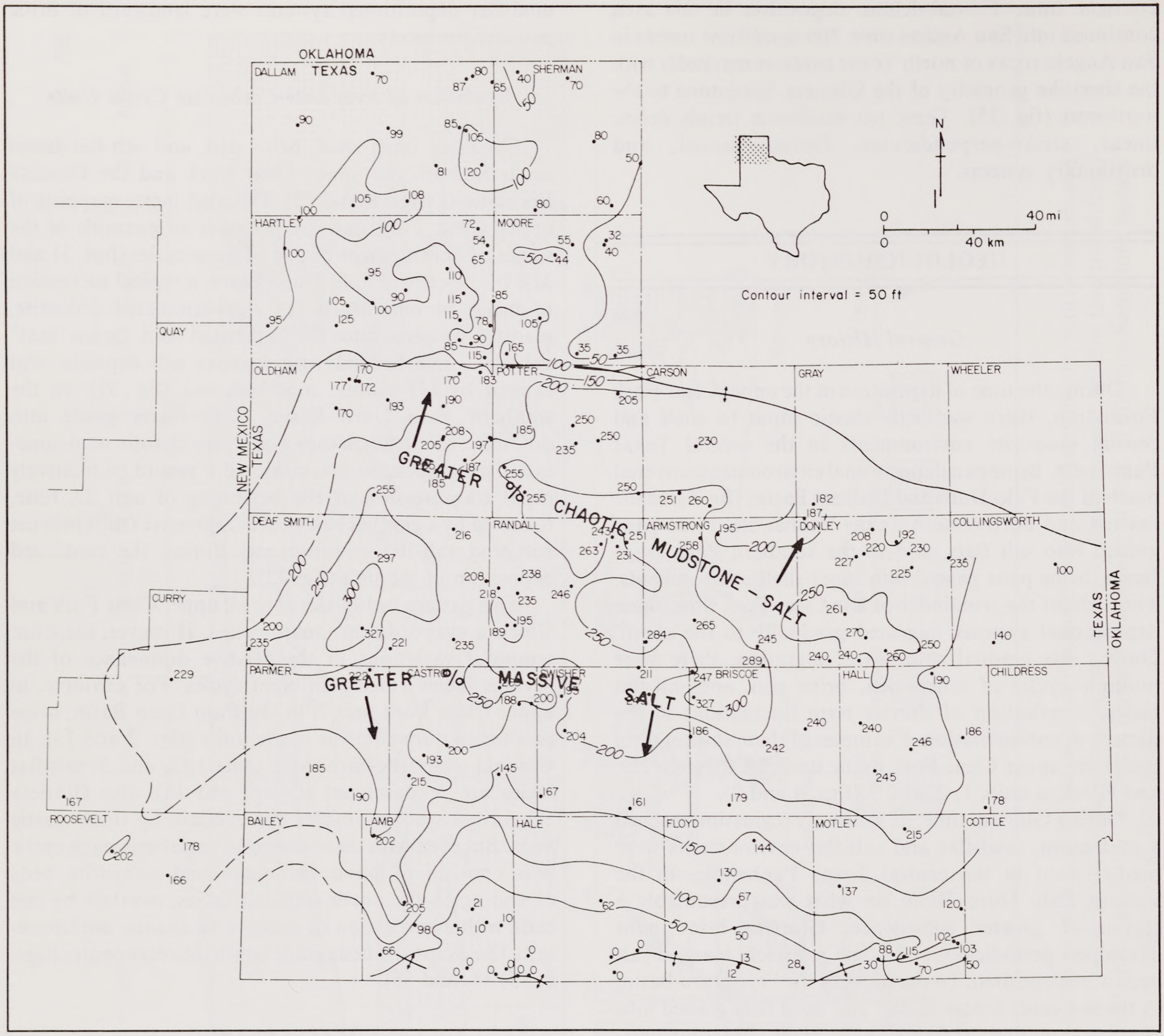


Figure 28. Net salt in upper Clear Fork Formation, Palo Duro and Dalhart Basins. Values are determined from gamma-ray logs. Because salt-bearing rocks are predominantly salt and mudstone, a line drawn midway between average (mode) high radioactivity (shale line) and minimal radioactivity (anhydrite line) on gamma-ray curves can be used statistically to separate mudstone from salt. Parts of the gamma-ray curve having radioactivity less than the midway line are considered salt. Net salt on this map is summation of these low-radioactive intervals; low-radioactive beds of anhydrite and dolomite are not included in net-salt totals. Where net salt is thick, massive salt beds predominate.

southward to the Bailey trend by progradation of successive mud-flat units. As evidence, unit A exhibits a thickening at the Castro trend only; unit B is thick in both centers, and unit C is thick only along the Bailey trend (fig. 36).

Periodically, in Glorieta time, the rate of deposition of clastics in mud flats diminished and evaporites were deposited; then mud-flat platforms served as subtle topographic restrictions that controlled the distribution of evaporite facies (figs. 36 and 37). Inner-shelf environments seaward of the mud flats graded into brine pan and salt-flat systems, which developed on the mud-flat surfaces. As mud flats migrated progressively seaward throughout Glorieta time, evaporite facies kept pace with the mud flats and also migrated seaward.

Controls of Facies Variations

Cyclicity and facies variations in upper Clear Fork and Glorieta rocks may have been controlled by a

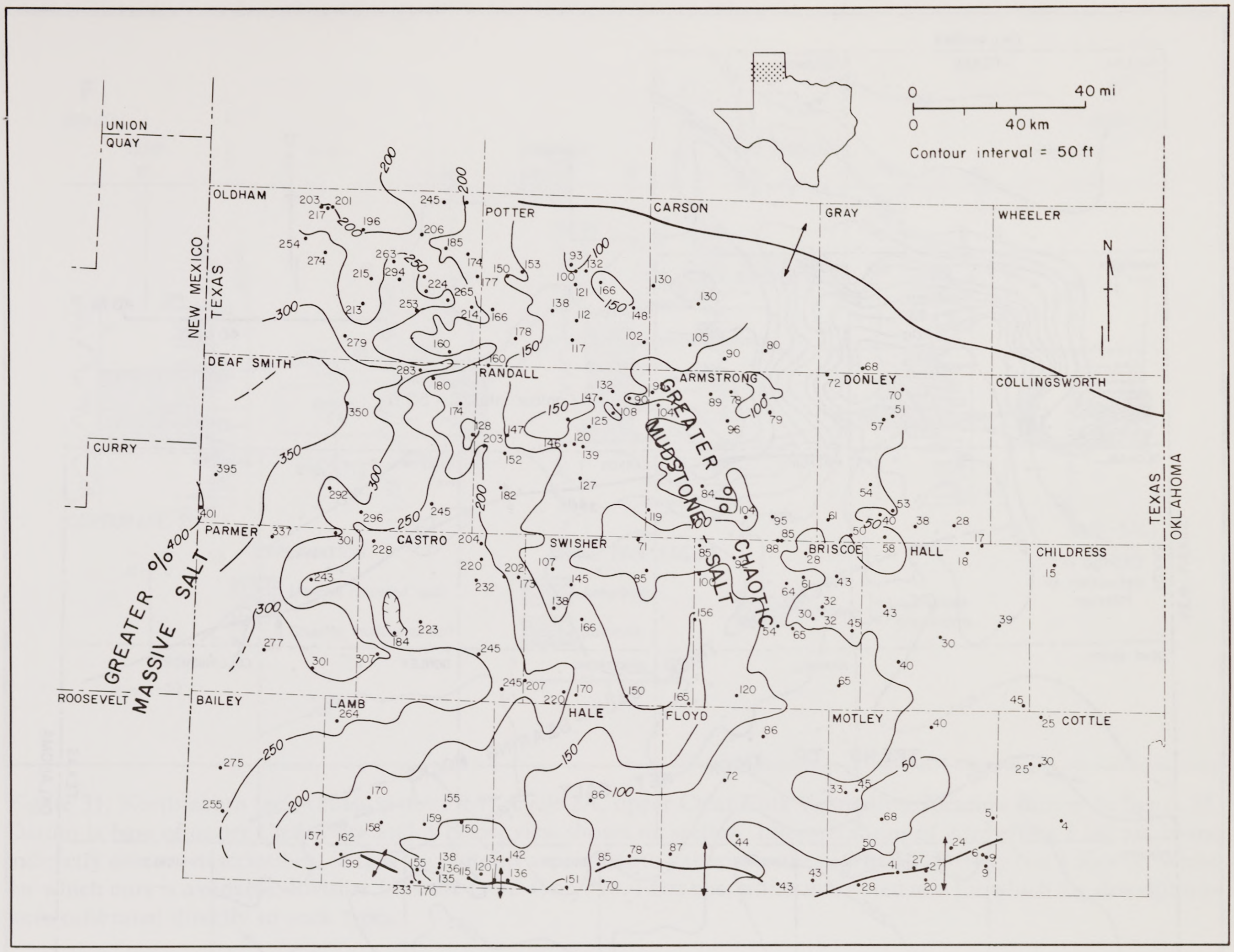


Figure 29. Net salt in Glorieta Formation, Palo Duro Basin. Values determined from gamma-ray logs. Net salt increases to west, following isopach patterns for formation as a whole (fig. 12). Massive salt beds tend to be more abundant to west in areas of thicker net salt.

combination of (1) basin subsidence, (2) eustatic sea-level changes, (3) progradation/aggradation of sedimentary facies, and (4) clastic sediment supply.

1. *Basin subsidence.* Centers of thickening of the upper Clear Fork and Glorieta Formations gradually shifted from the central to the western Palo Duro Basin, as illustrated on isopach maps (figs. 11 and 12). Changing patterns of upper Clear Fork-Glorieta paleogeography followed the westward shift in centers of thickening, as is evident from paleogeographic and lithofacies maps (figs. 5, 28, and 29). Given that upper Clear Fork-Glorieta sedimentation was on a relatively low-relief surface, centers of thickening must reflect centers of greatest subsidence. Brine pan facies, which developed in relative topographic depressions (considered low-relief depressions), consistently occur at the centers of thickening. This suggests that brine pan depressions were also controlled by subsidence.

2. *Eustatic sea-level changes.* Eustatic changes in sea level have been a favorite explanation for cyclicity in late Paleozoic time (Wanless, 1972; Wilson, 1975). The mechanism considered by many to be the control of these eustatic sea-level changes has been late-Paleozoic continental glaciation (Wilson, 1975). Silver and Todd (1969) favored glacially controlled eustatic sea-level variations as the cause of Early to Middle Permian cyclic deposition in the Permian Basin of Texas and New Mexico. They noted that cycles of equivalent age are observed worldwide (Silver and Todd, 1969). In the Texas Panhandle, where we have studied these Permian rocks, cyclic units can be mapped from basin margin to basin margin and across uplifts into adjacent basins. This is a pattern that would be expected from regional sea-level variations rather than from crustal subsidence, which tends to vary from basin to basin and across uplifts.

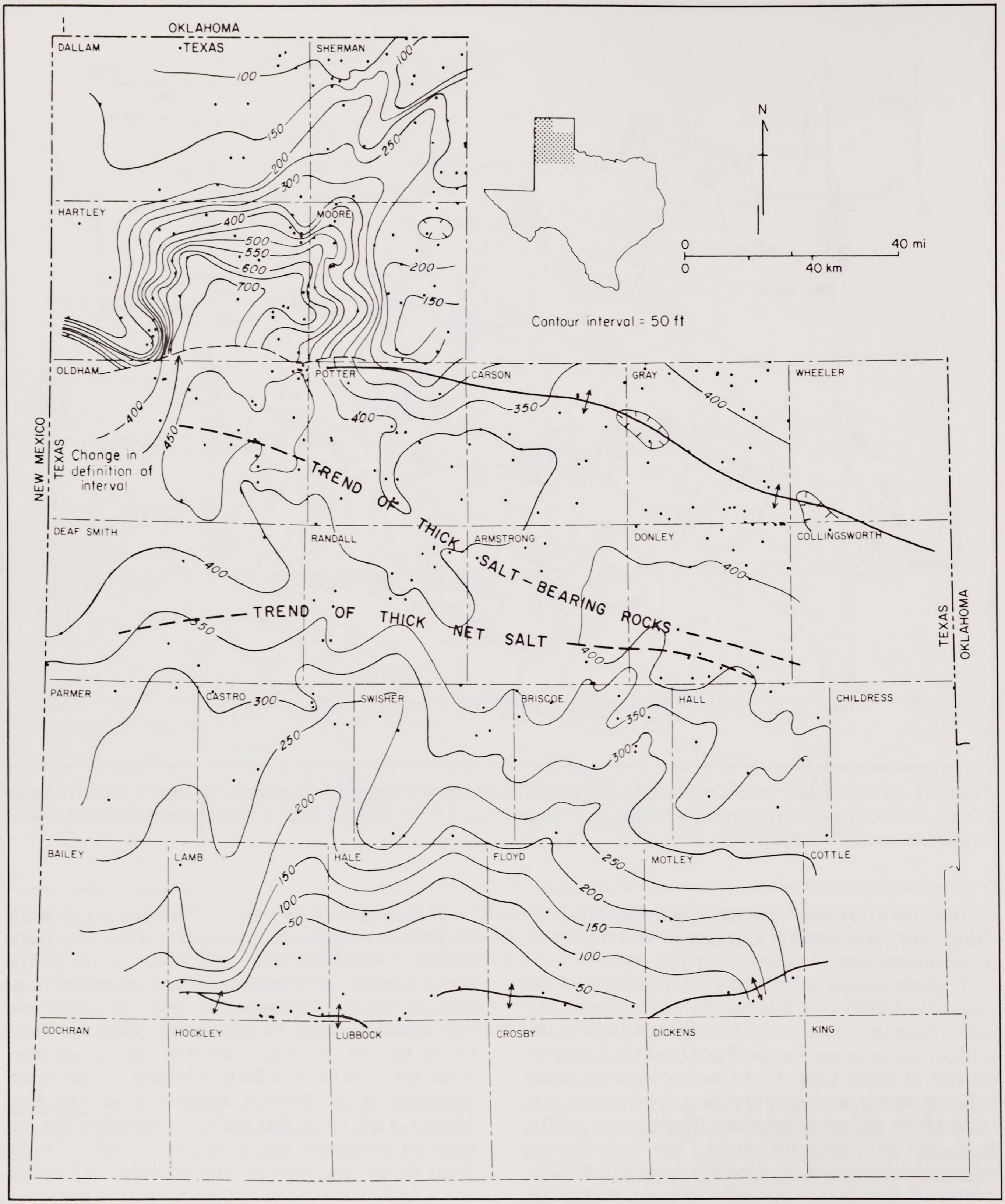


Figure 30. Thickness of salt-bearing rocks in upper Clear Fork Formation, Palo Duro and Dalhart Basins. Values are total thickness of rocks that contain salt. In general, more massive salt beds occur to south; mudstone-salt lithologies occur to north. Because thick beds of mudstone-rich salt are included in the total of salt-bearing rocks, thickest values of net salt-bearing rocks occur north of thickest net salt (compare figs. 28 and 30). In Dalhart Basin, thickness of salt-bearing rocks (interval is dominantly mudstone) is shown for combined upper Clear Fork and Glorieta Formations.

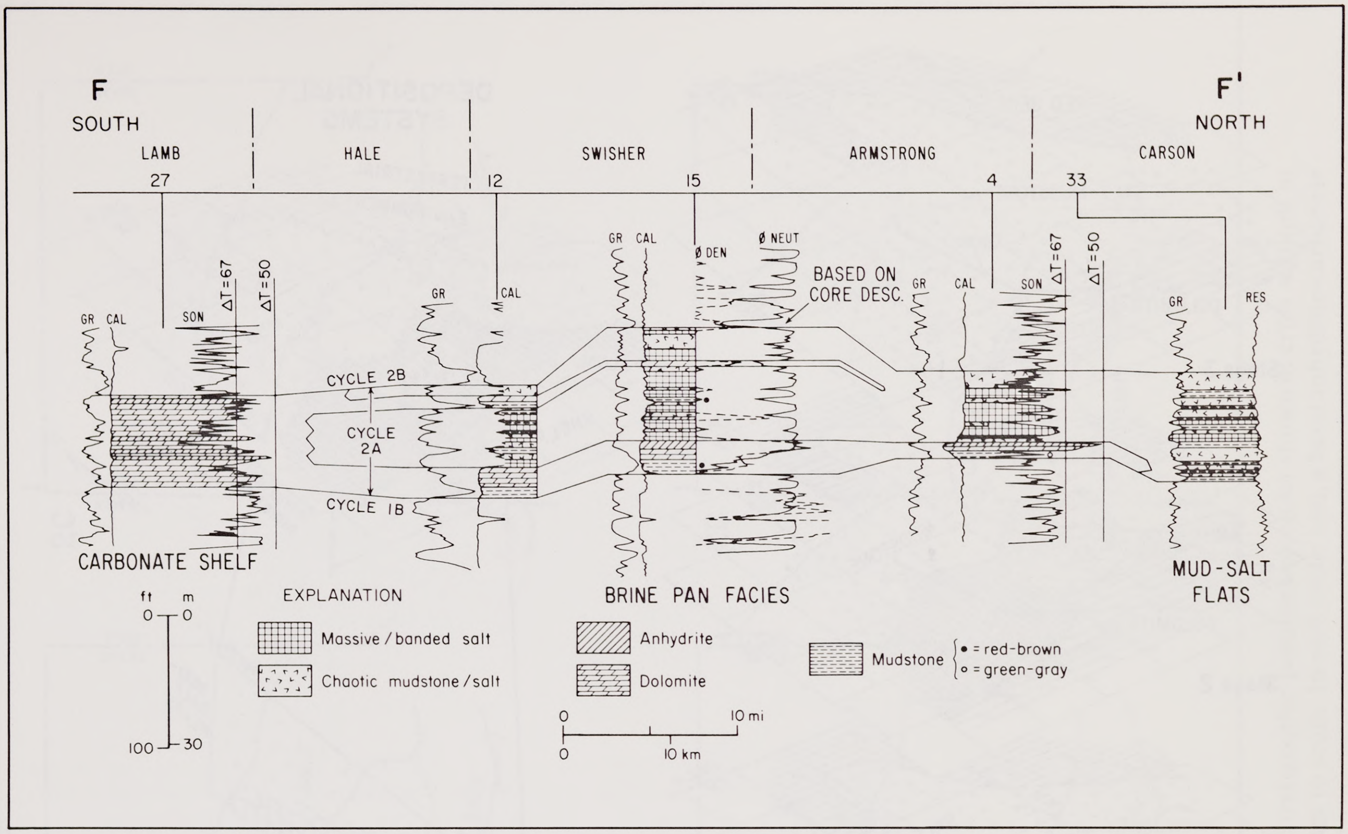


Figure 31. North-south facies cross section F-F′, cycle 2A, upper Clear Fork Formation, location shown on figure 32. Datum is base of upper Clear Fork and is below view shown on section. Interpretations of Armstrong 4 log are based indirectly on core descriptions, in that log patterns are similar to patterns in the nearby DOE-Gruy No. 1 Rex H. White for which core is available. Swisher 14 is the DOE-Gruy No. 1 Grabbe, which was cored and for which log descriptions were calibrated directly to rock types.

3. *Progradation/aggradation of sedimentary facies.* Carbonate and clastic environments in the Texas Panhandle in Permian time were commonly progradational, aggradational, or both. In a general sense, one trend of sedimentation was a continuous process of constructing and maintaining a "supratidal" surface in coastal environments. During subsidence or a rise in sea level, these constructional systems adjusted landward. Then these systems shifted progressively seaward as the sea level stabilized and carried evaporite systems with them. The beginning of a cycle of deposition in upper Clear Fork-Glorieta rocks may have been caused by eustatic sea-level changes; however, the subsequent pattern of regressive sedimentation in this cyclicity can be explained largely by sedimentary processes.

4. *Clastic sediment supply.* Rates of clastic input into coastal depositional systems controlled the position of upper Clear Fork-Glorieta facies. During deposition of unit 1 of the upper Clear Fork Formation, rates of clastic input were low, and brine pan depositional systems were predominant in the central Panhandle (fig. 38). As upper Clear Fork deposition progressed, the percentage of clastics relative to evaporites increased, particularly in the northwestern Texas Panhandle (fig. 38). With the increase in clastics, brine pan and shelf environments were limited to the central and southern Palo Duro Basin, to the south of regions with clastic infilling (fig. 5). During Glorieta time, input of clastics to the study area increased significantly, and salt- and mud-flat depositional systems were predominant over most of the Panhandle. Brine pan deposition was strictly limited.

CONCLUSIONS

Upper Clear Fork and Glorieta evaporite and carbonate facies were deposited in a range of shallow marine-shelf and intertidal to supratidal evaporite environments along an arid coastline. In inner-shelf environments, carbonates were deposited in upward-shoaling successions of subtidal, intertidal, and supratidal facies. Evaporites were deposited on a broad low-relief salt plain landward of shelf environments. Seaward parts of the salt plain were commonly flooded with hypersaline brines, creating broad shallow-water

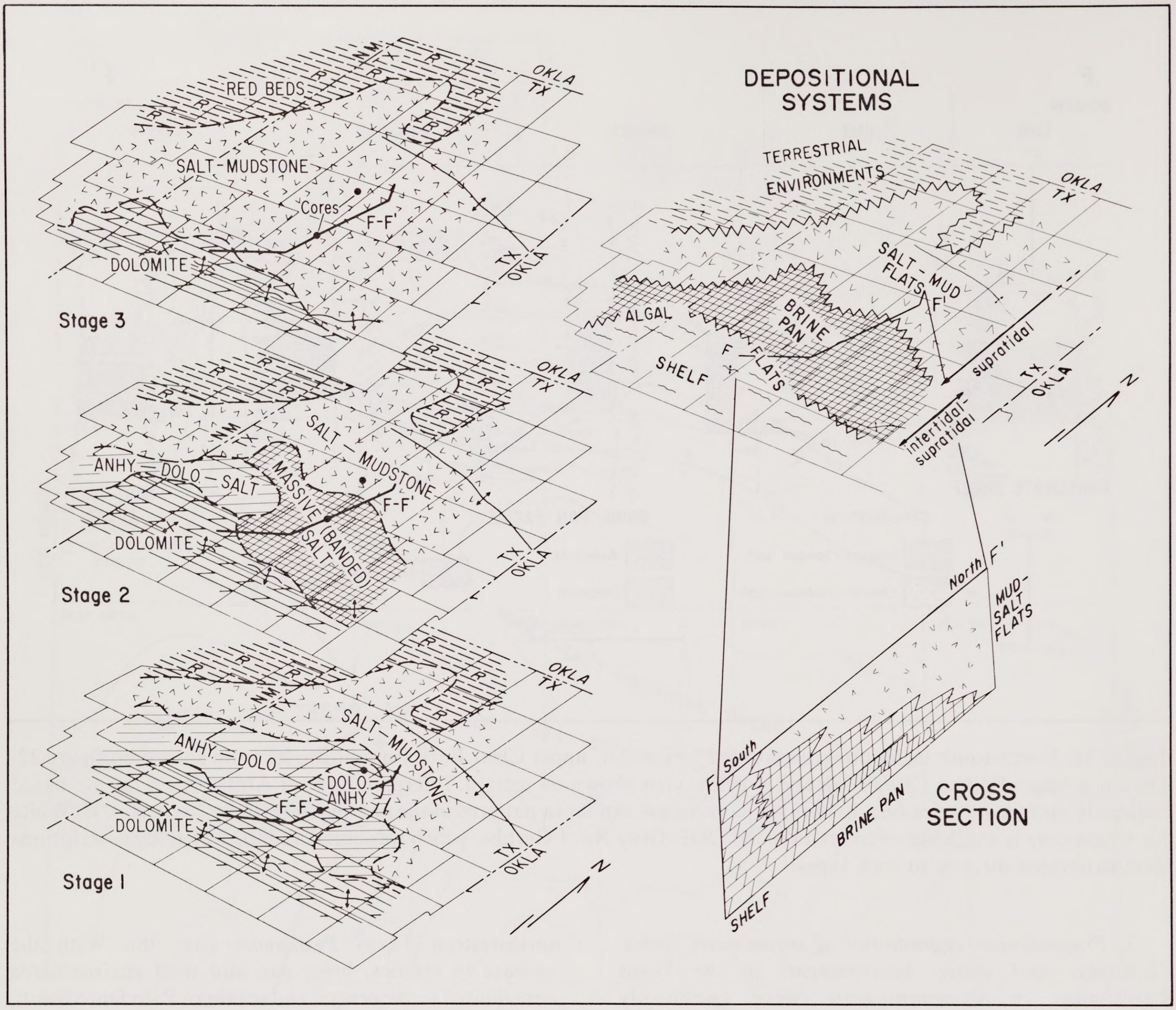


Figure 32. Facies maps, cycle 2A, upper Clear Fork Formation. Maps show facies during early, middle, and late stages of development. Generalized depositional systems are keyed to interpretations on figure 3. Details of cross section are shown in figure 31.

brine pans in which subaqueous evaporite facies such as laminated sulfates, "grass mat" gypsum, and relatively pure halite were deposited. Landward parts of the salt plain were filled in by muds and silt and were commonly exposed. Precipitation of evaporites in these subaerial environments was interstitial and possibly was in surface salt crusts. Salt-flat facies are chaotic mixtures of mudstone and salt. Evaporite environments passed landward into arid terrestrial environments.

Periodically, evaporite-carbonate sedimentation was interrupted by the development of broad mud-rich tidal flats that extended across the entire salt plain. Mud-flat facies are composed predominantly of mudstone and interlaminated mudstone-siltstone. To the south of the Palo Duro Basin, mud flats graded into littoral and marine-shelf environments where sandstone and carbonates were deposited. To the northwest and east of the Texas Panhandle, mud flats passed into terrestrial environments.

The upper Clear Fork and Glorieta Formations in the Texas Panhandle constitute a single lithogenetic unit that exhibits a broad cycle of southerly regression. Within this lithogenetic unit, carbonates deposited in marine environments grade upward and landward (to the north) into intertidal to supratidal evaporites and red beds. Upper Clear Fork facies in the central Texas Panhandle indicate a dominance of carbonate and evaporite (inner-shelf, brine pan, and salt-flat) environments early in the

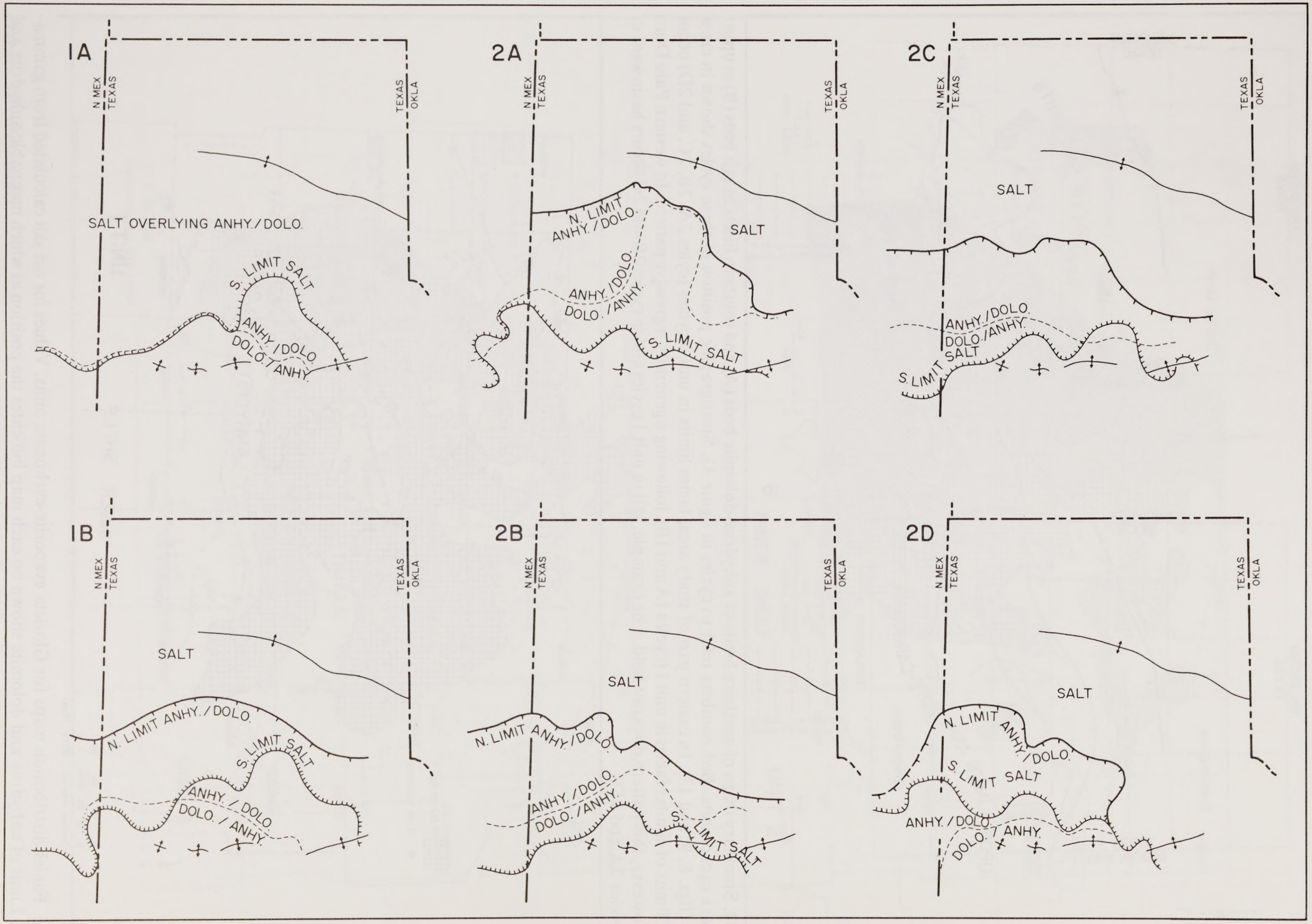


Figure 33. Distribution of facies in upper Clear Fork cyclic units. Stratigraphic positions of cycles shown in cross sections in figures 8, 9, and 13. Salt is dominant to north; carbonates are dominant to south. In each cyclic unit, a basal anhydrite-carbonate bed extends north beneath salt facies.

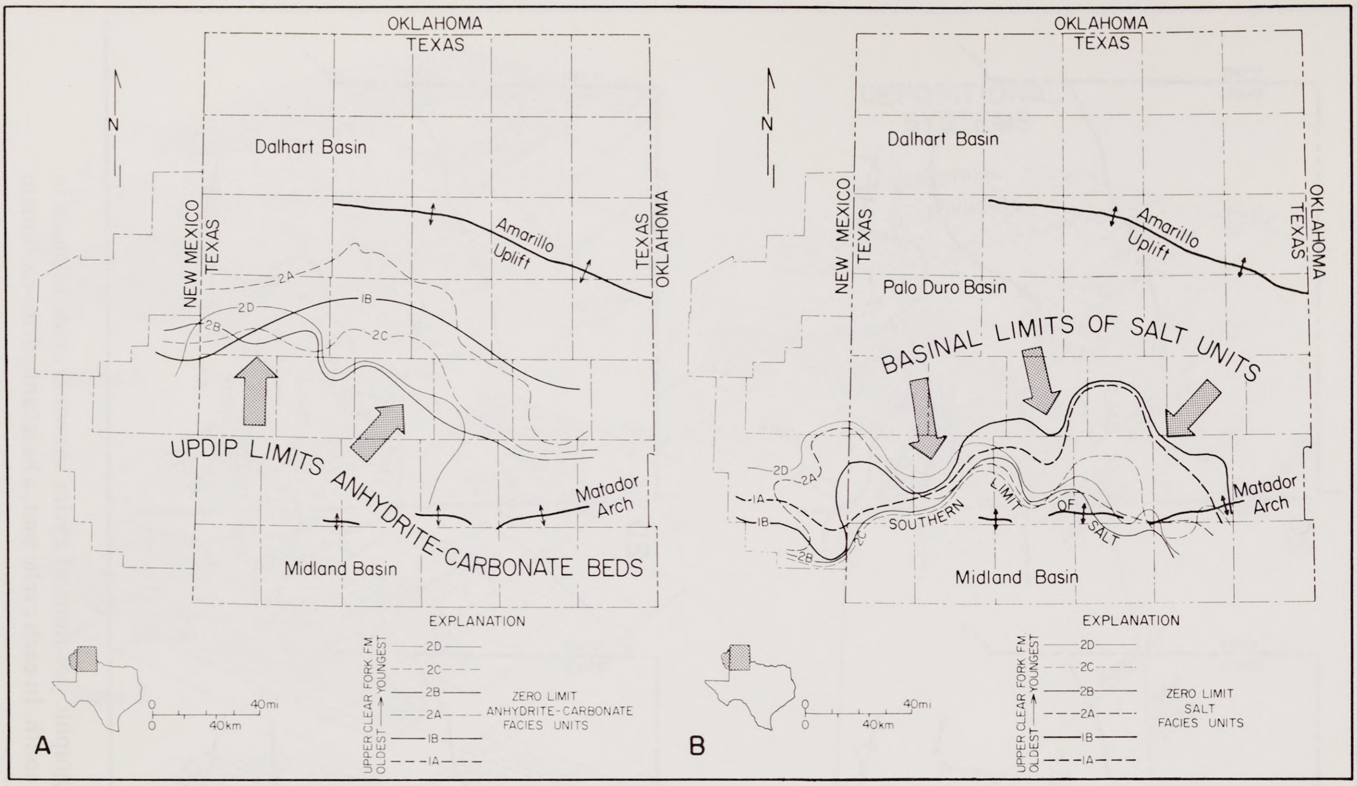


Figure 34. Summary maps of northern limits of anhydrite-dolomite beds (A) and southern limits of salt beds (B) in upper Clear Fork cyclic units. Bed numbers refer to cycles in figure 33. Stratigraphic position of these cycles shown in cross sections (figs. 8, 9, and 13). In eastern part of study area, facies limits in unit 2 cycles (cyles 2A, 2B, 2C, and 2D) occur south of limits of similar facies in unit 1 (cycles 1A and 1B), following a generally regressive pattern. In western Palo Duro Basin, however, this pattern does not hold. For example, salt in unit 1 cycles and in cycles 2B and 2C occurs basinward of salt in cycles 2A and 2D.

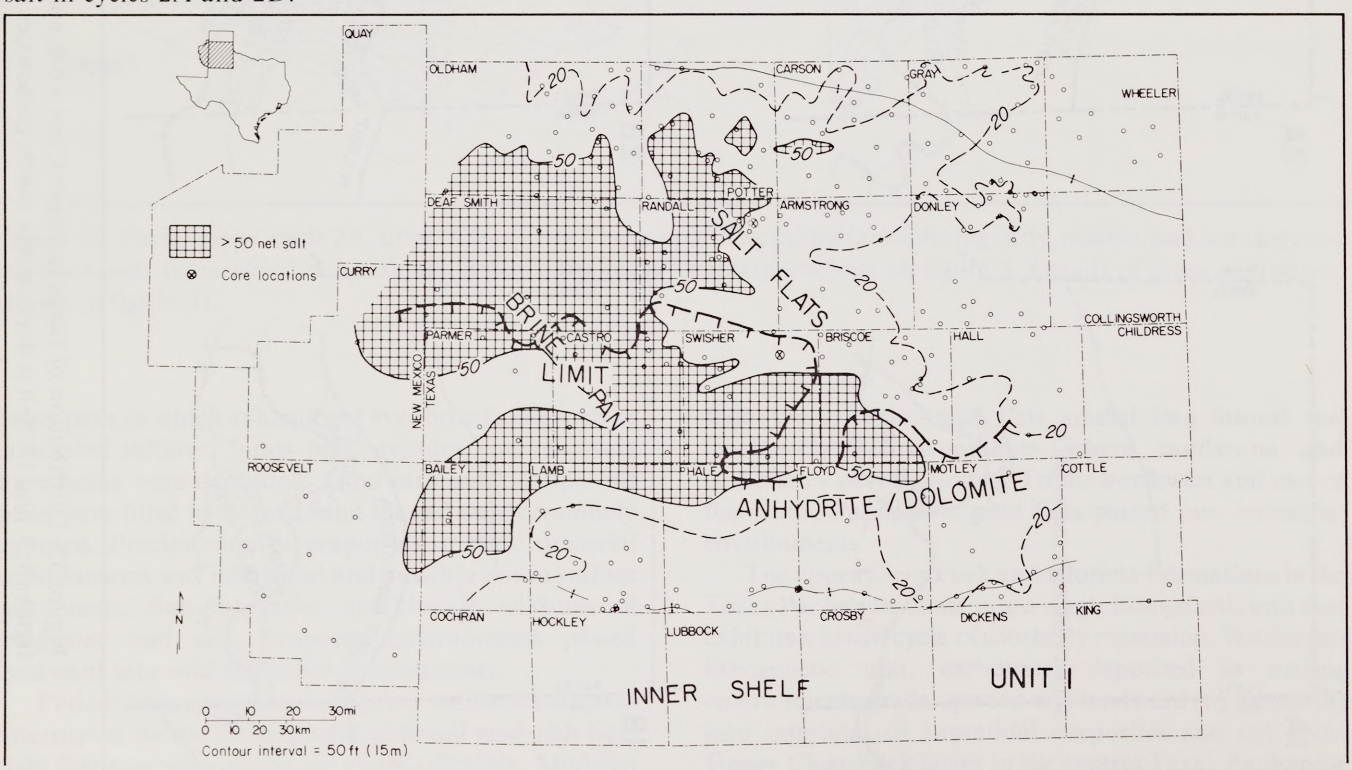
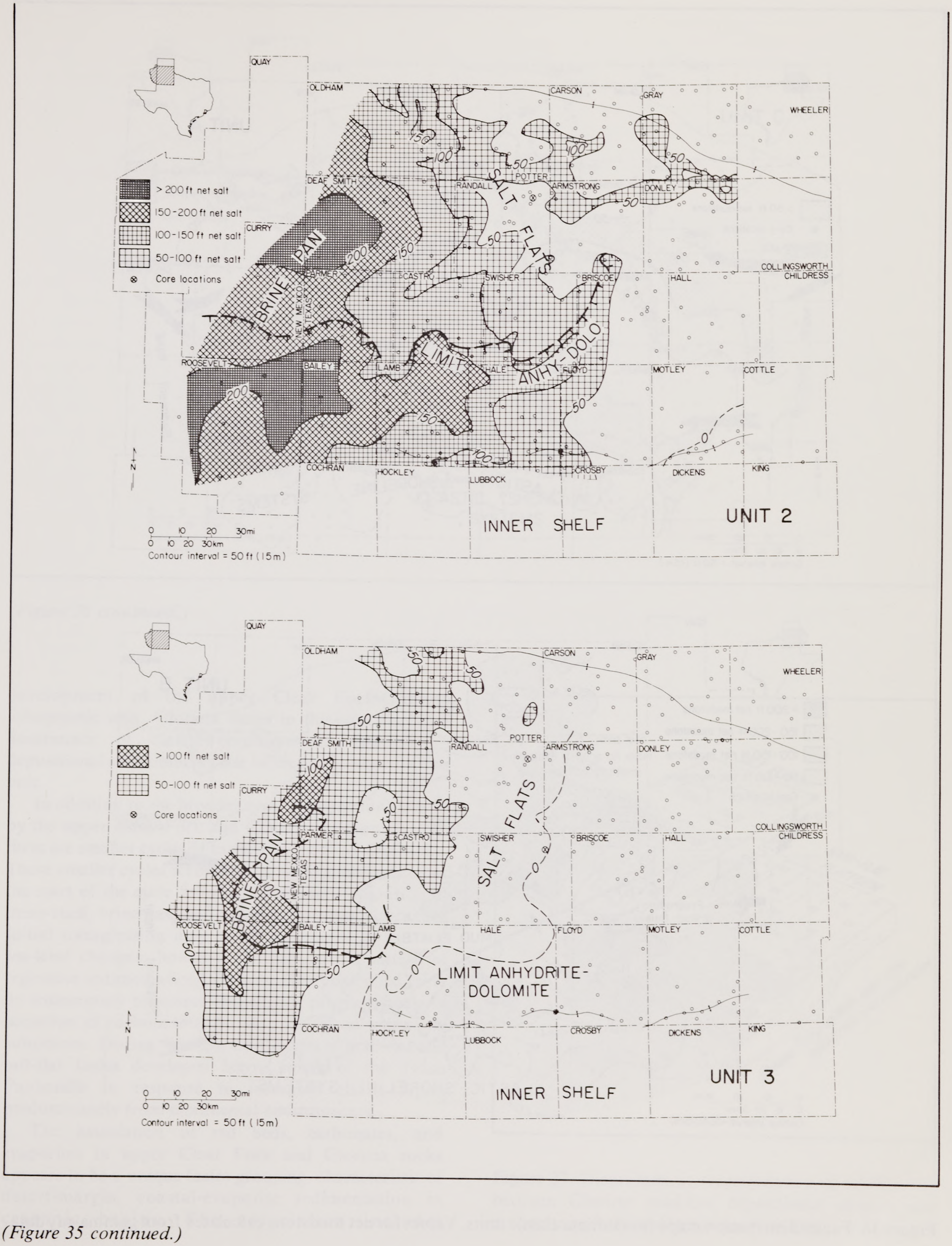


Figure 35. Facies distribution maps for Glorieta evaporite-carbonate units. Values for net salt calculated from gamma-ray data. Limit of anhydrite and dolomite shown on each map indicates the position at which mappable anhydrite and dolomite beds pinch out toward the north within the respective units.



(Figure 35 continued.)

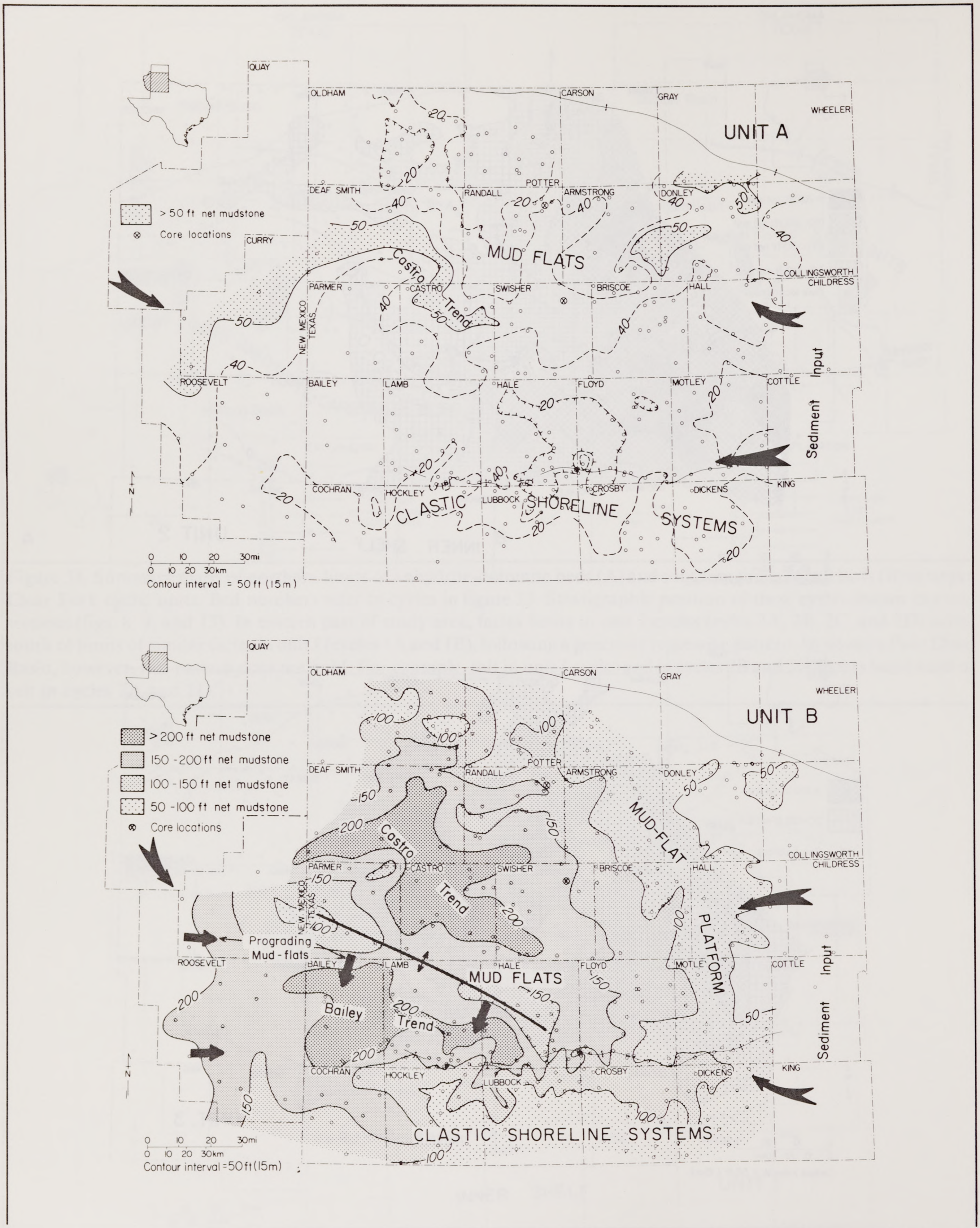
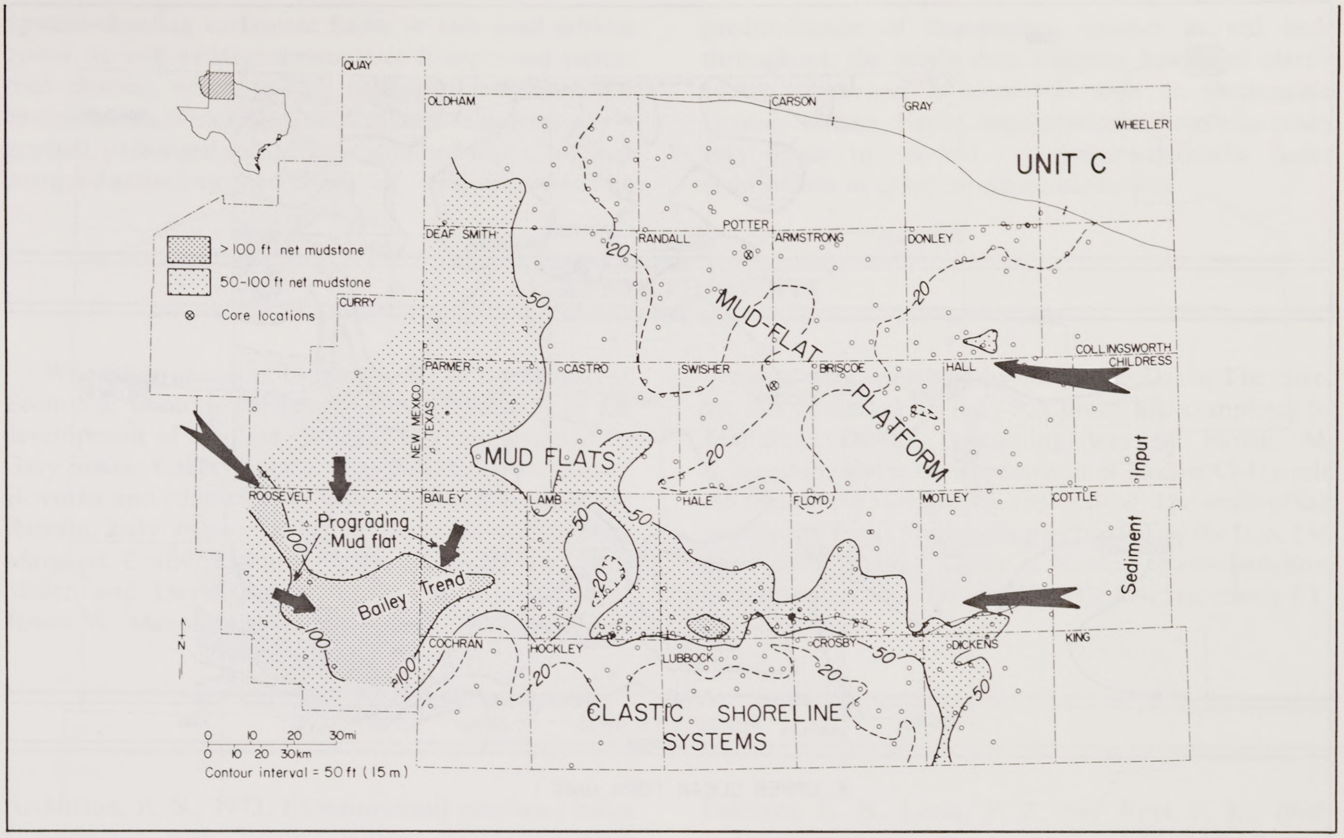


Figure 36. Facies distribution maps for Glorieta clastic units. Values for net mudstone calculated from gamma-ray data.



(Figure 36 continued.)

development of the upper Clear Fork-Glorieta lithogenetic unit. Glorieta facies in this area record a dominance of clastic (mud-flat and terrestrial) depositional environments late in the development of this unit.

In addition to the broader cycle of regression evinced by the upper Clear Fork and Glorieta lithogenetic unit, there are smaller cycles of carbonate and evaporite facies. These smaller cycles record initial rapid transgression at the start of the cycle followed by seaward migration of inner-shelf, brine pan, and salt-flat depositional systems. Initial transgression may have been caused by eustatic sea-level changes; however, the subsequent pattern of regressive sedimentation may have been controlled more by sedimentary processes of shoreline progradation and accretion of carbonate and clastic facies, as well as by subsidence. During Glorieta time, cycles of mud-flat and salt-flat facies developed across much of the Texas Panhandle in response to increased clastic input, predominantly from continental environments.

The association of red beds, carbonates, and evaporites in upper Clear Fork and Glorieta rocks appears to be a unique facies grouping, characteristic of desert-margin, coastal-evaporite sedimentation in cratonic basins. The association includes

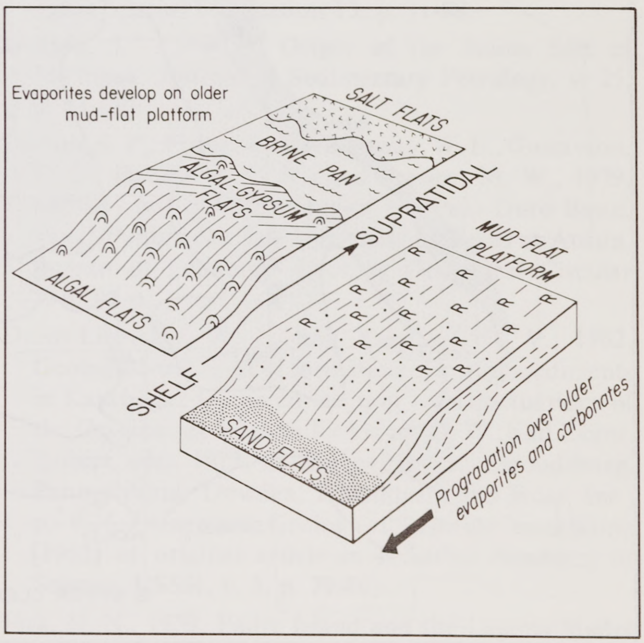


Figure 37. Diagrammatic representation of relationship between Glorieta mud-flat depositional systems and evaporite-carbonate depositional systems.

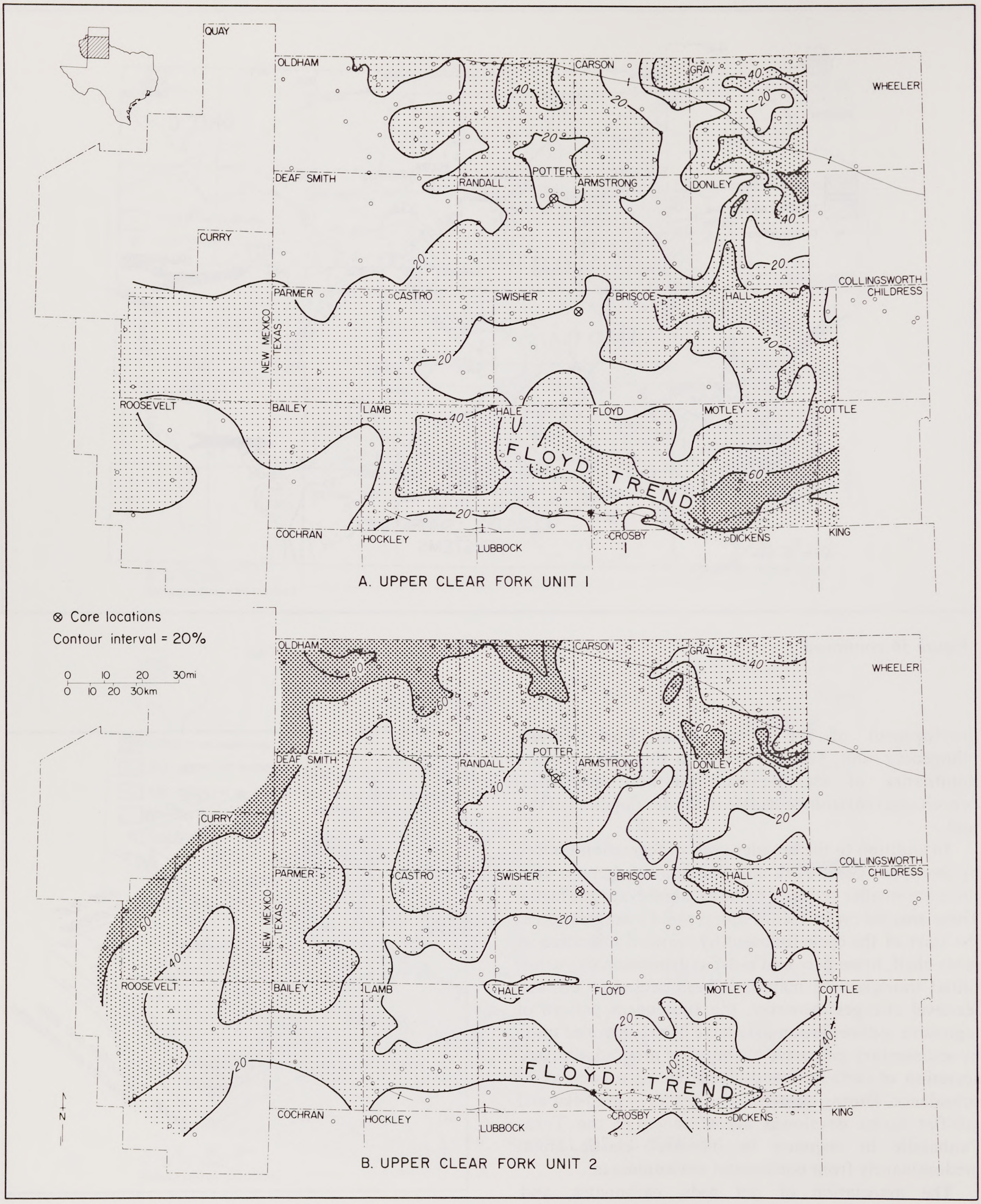


Figure 38. Percent mudstone in upper Clear Fork units 1 and 2 (maps A and B, respectively). Values were calculated from gamma-ray data. Thicker net mudstone along Floyd trend is a record of clay in inner-shelf depositional systems. Mudstone in central and northern Palo Duro Basin is predominantly in salt-flat and mud-flat depositional systems.

upward-shoaling carbonate facies in lime mud-sabkha cycles, as well as large amounts of fine-grained terrestrial clastics, which infilled and aggraded supratidal environments. Thick sequences of such sediments imply gradual, prolonged subsidence combined with continued progradation/aggradation of sediments. The predominance of fine-grained clastics in red beds throughout the study area suggests low-relief clastic source areas and is consistent with an epiorogenic tectonic setting. Facies interpretations from this study may apply to red-bed - carbonate-evaporite facies associations in other intracratonic basins.

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